CHAPTER 2

WATER QUALITY PARAMETERS

Section I. Introduction

2-1. Definition of Water Quality. Water quality, as defined in this manual, is composed of the physical, chemical, and biological characteristics of water and the abiotic and biotic interrelationships.

2-2. Reservoir-Watershed Relationship.

a. Any reservoir or stream system is coupled with its watershed or drainage basin. Therefore, basin geometry, geology, climate, location, and land use are integral factors that directly or indirectly influence stream or reservoir water quality. Conversely, water quality changes in reservoirs are the result of physical, chemical, and biological loading, generally through runoff and/or stream transport and processing.

b. In a dam/reservoir project area, the Corps owns a limited quantity of the surrounding land. As a result, the water quality of a particular reservoir is often controlled by a watershed, and/or activities therein, over which the Corps has little or no control. In turn, many water quality problems in the reservoir cannot be dealt with directly but must be handled by or through a local, state, or other Federal entity. However, one should not assume that all water quality problems are the result of the watershed characteristics alone. Many water quality problems result from structures associated with the dam, project operation, or the reservoir itself. Solutions to these problems are within the control of the Corps.

Section II. Reservoir Description

2-3. Definition. In limnological terminology (study of freshwater bodies), reservoirs are defined as artificial lakes. All standing waters were classified as lakes as far back as the 1890's by the pioneer limnologist Forel. More recently, lakes have been classified into 76 types, with reservoirs as one type of lake produced by higher organisms, that is, man (see Ref. 77).

2-4. Comparison to Natural Lakes. In some ways, reservoirs can be considered as having the characteristics of only one-half of natural lakes. That is, the deepest portion of a natural lake may be located anywhere, but is often near the center, with all portions of the lake bottom sloping toward that maximum depth. By contrast, the deepest portions of reservoirs are almost always near the dam, and the reservoir bottom usually slopes toward the dam. Also, the inlet and outlet of natural lakes are near the surface, whereas a reservoir can release water from any location, ranging from the surface to the deepest portion of the impoundment. Consequently, although the limnological processes determining water quality conditions are the same in both cases, the hydrodynamics of reservoirs make their water quality characteristics different than those of natural lakes. From an ecological point of view, a reservoir normally has variable productivity potential levels--high in the early years, low during the following years and then, sometimes, high again during the reservoir's mature stage. By contrast, the natural lake follows a successional pattern from oligotrophy to eutrophy.

2-5. Classification of Reservoirs. Reservoirs, especially natural lakes, have been classified using a variety of systems, including physical, chemical, and geomorphological characteristics, and indicator species or species aggregates. This section presents a brief overview of the classification systems commonly used within the Corps.

a. Stratified Versus Unstratified. Reservoirs may or may not stratify, depending on conditions such as depth, wind mixing, and retention time (see para 2-7d). Under appropriate conditions, the reservoir will form an epilimnion or upper layer, a metalimnion or transitional layer, and a hypolimnion or lower layer. However, if conditions do not allow stratification, the entire reservoir may consist of an epilimnion with an isothermal gradient. The stratified or unstratified condition can dramatically affect water quality conditions of the reservoir and its releases. Releases from an unstratified reservoir, irrespective of the withdrawal level, will generally be warmwater releases; bottom-level withdrawals from a stratified reservoir will be generally coldwater releases. Warm and cold releases, in the sense of this discussion, are relative to the water temperature of the stream into which the releases are made. Additional aspects of water quality conditions associated with stratified or unstratified conditions will be discussed in subsequent sections.

b. Operational Characteristics.

(1) General. Reservoir projects are authorized for a variety of purposes, the most common of which are flood control, navigation, hydroelectric power generation, water supply, fish and wildlife conservation and enhancement, recreation, and low-flow augmentation. Since the mid-1970's, Corps reservoirs also have water quality enhancement as an authorized project purpose. Today, most reservoirs are authorized as multiple-purpose projects, with storage allocated for two or more purposes. Multiple-purpose reservoirs, operated either separately or as a system, often result in conflicting uses for reservoir storage.

(2) Flood control. Use of a reservoir for flood control consists of storing water in excess of the downstream channel capacity (damaging flows) during flood periods for later release during periods of flow at or below channel capacity (nondamaging flows) at a downstream control point. Since a major factor in flood control reservoirs is maintaining available volume (i.e., empty storage space) for flood storage, the flood control purpose generally is the least compatible with other project purposes.

(3) Navigation. Reservoir projects operated for navigation purposes are directed at providing sufficient downstream flow to maintain adequate water depth for navigation and/or providing sufficient water volume for lockages. In many navigation projects, the reservoir pool is a part of the channel, so pool levels must be controlled to provide both sufficient navigation depths within the pool and downstream depths. Downstream releases for navigation purposes may have a distinct seasonal pattern, with higher releases required during the dry season.

(4) Hydroelectric power generation.

(a) Hydroelectric power generation consists of passing water through turbines to produce electricity. Hydroelectric facilities normally are operated to produce two types of power: baseload power and peak power. Baseload power is firm power generated to supply a portion of a constant daily demand for electricity. Peaking power is power supplied above the baseload to satisfy variable demands during periods of heavy electricity usage. Reservoir releases to meet baseload power are generally constant over several hours, while those designed for peaking power will fluctuate by the hour.

(b) The power output of a facility is determined by the flow through the turbine and the head or pressures exerted on the turbine. Therefore, it is advantageous to have hydroelectric power reservoirs at maximum storage or full pool for maximum power generation. This is best accomplished by pumped-storage hydropower reservoirs which maintain a full pool by pumping previously released water back into the reservoir following generation. Electricity is generated and used during high-demand periods (i.e., high market value) to provide energy to consumers; it is used to pump water back into the reservoir during low-demand periods when energy costs are lower. Most hydroelectric power plants are part of either an interconnected system or a power grid so that flexibility in coordinating generation releases with other water uses is possible.

(5) Water supply. Reservoirs with water supply objectives store water during periods of excess inflow for use during other periods. Withdrawal may take place directly from the reservoir, or in downstream reservoir releases. Water is generally provided to municipal, industrial, or agricultural users as reservoir storage rather than by contract to supply a specific volume of water. Consequently, water supply can be obtained by a user from the reservoir as long as there is sufficient water in that particular segment of storage. Adequate reserve storage is usually maintained to avoid water shortages during drought periods.

(6) Fish and wildlife conservation and enhancement. Reservoirs used for fish and wildlife conservation and enhancement may include features such as intake structures to minimize entrapment and entrainment of fish and other aquatic species; outlet and emergency spillway structures to minimize contact of aquatic species with waters supersaturated with dissolved gases and to provide appropriate release water quality; and fish ladders, fish bypasses, and

other pertinent facilities to permit fish passage around structures. Fish and wildlife habitat at these reservoirs is improved by retaining standing vegetation during construction, as well as providing conditions conducive to growth of suitable aquatic and wetland vegetation.

(7) Recreation. Recreation activities in and around reservoir projects include camping, picnicking, fishing, pleasure boating, water skiing, swimming, and hunting. Similar activities also take place downstream of the reservoir in and adjacent to the tailwater. Recreational users of both areas generally prefer constant water levels.

(8) Low-flow augmentation. Low-flow augmentation reservoirs provide releases that increase flow in the downstream channel for downstream fish and wildlife purposes or for downstream water quality control. Storage allocation for downstream water quality control currently can be obtained only under special circumstances.

c. Trophic Status.

(1) Reservoirs are commonly classified or grouped by trophic or nutrient status. The natural progression of water bodies through time is from an oligotrophic (i.e., low nutrient/low productivity) through a mesotrophic (i.e., intermediate nutrient/intermediate productivity) to a eutrophic (i.e., high nutrient/high productivity) condition. The prefixes "ultra" and "hyper" are sometimes added to oligotrophic and eutrophic, respectively, as additional degrees of trophic status. The tendency toward the eutrophic or nutrient-rich status is common to all impounded waters.

(2) The eutrophication or enrichment process has received considerable study because:

(a) It can be accelerated by nutrient additions through cultural activities (e.g., point-source discharges and nonpoint sources such as agriculture, urbanization, etc.).

(b) Water quality conditions associated with eutrophication may not be desired.

(c) To a certain degree, cultural eutrophication impacts are reversible.

(3) The majority of reservoir water quality conditions relate to the eutrophication process. Certain physical, chemical, and biological factors change during eutrophication (Table 2-1). Quantitative criteria for these factors have been developed to define various trophic states, but the ranges are broad and may not reflect geographic/demographic differences in water quality. (Additional discussion of eutrophication can be found in Refs. 43, 44, 45, and 110 and in Item ff of Appendix B.)

TABLE 2-1

Selected Trophic Indicators and Their Response to Increased Eutrophication[1]

Physical	Chemical	Biological
Transparency (D) (Secchi disk depth)	Nutrient concentrations (I) (e.g., at spring maximum)	Algal bloom frequency (I)
Suspended solids (I)	Chlorophyll *a* (I)	Algal species diversity (D)
	Conductivity (I)	Littoral vegetation (I)
	Dissolved solids (I)	Zooplankton (I)
	Hypolimnetic oxygen deficit (I)	Fish (I)
	Epilimnetic oxygen supersaturation (I)	Bottom fauna (I)
		Bottom fauna diversity (D)
		Primary production (I)
		Phytoplankton biomass (I)

[1] (I) = Increased, (D) = decreased.

Section III. Reservoir Characteristics and Processes

2-6. General.

a. Reservoir water quality is a system response to the reservoir's watershed, the region's climate, as well as the geometry and internal characteristics and processes of the reservoir. Water quality is affected by the type, location, and manner of operation of the reservoir's water control facilities. Macro- and micro-meteorological forces, inflows, internal processes, outflows, and project operation are highly dynamic and can be dominant factors in determining the water quality in a reservoir. To understand why certain water quality conditions develop, one must understand the interaction of all the dynamic phenomena influencing the reservoir and its associated waters.

b. This section introduces some of the important characteristics and processes that influence the quality of water in reservoirs. For simplicity, relevant limnological factors are categorized as being physical, chemical, or biological in nature. Such separation does not occur in nature; the factors are all interrelated. Thus, it must be understood that many factors discussed could fall into more than one category. (Additional information on limnological processes and terminology can be found in Refs. 77, 78, and 110.)

2-7. Physical Characteristics and Processes.

a. Site Preparation. Depending upon the planned reservoir uses, site preparation (e.g., topsoil stripping, timber removal) may have a significant effect upon water quality after inundation. Additional information on the subject may be found in Refs. 13 and 71.

b. Morphometry.

(1) Morphometric variables that can influence hydrologic and limnologic characteristics of the reservoir include surface area, volume, mean depth, maximum depth, shoreline development ratio, and fetch. Formulas for computing the values of these and other characteristics are given in Table 2-2. Biological productivity, respiration, decomposition, and other processes influencing water quality are related directly or indirectly to reservoir morphometry. Morphometric characteristics themselves also are interrelated and provide insight into existing or potential water quality conditions. Mean depth, for example, is computed as volume/surface area (V/A); shallow mean depths may indicate light penetration to the bottom, warmer water temperatures, higher organic decomposition rates, and greater nutrient regeneration. All these factors can contribute to higher productivity. Lakes with shallow mean depths generally have higher biological productivity than lakes with deeper mean depths with comparable surface areas.

TABLE 2-2

Physical, Chemical, Morphometric, and Hydrologic Relationships*

Characteristics	Symbol	Formulation	Reference No.
Physical			
Water Density	ρ_w	$\rho_T + \Delta\rho_{TDS} + \Delta\rho_{SS}$	
- Thermal	ρ_T	$1,000 - \frac{(T - 3.98)^2 (T + 283)}{(503.57)(T + 67.26)}$	
- Total Dissolved Solids Increment	$\Delta\rho_{TDS}$	$\sim 0.00078 * C_{TDS}$	
- Suspended Solids Increment	$\Delta\rho_{SS}$	$\sim 0.00062 * C_{SS}$	
Settling Velocity (Stokes Law)	v_s	$\frac{gD^2}{18\nu} (\rho_s - \rho)$	106
Viscosity	ν	$\rho(0.069\ T^2 - 5.3T + 177.6)$	96
Sedimentation Index	S_I	$\tau(QL/V)$	75
Areal Erosion	$a_E + T$	$1,090\sqrt{A}/Z * \exp\ (Z/\sqrt{A})$	72

(Continued)

* Symbols used in this table are defined in Appendix D.

(Sheet 1 of 4)

TABLE 2-2 (Continued)

Characteristics	Symbol	Formulation	Reference No.
Morphometric/Hydrologic (Collated)			
Drainage Area	DA	-	
Surface Area (Normal Pool)	A	-	
Volume (Normal Pool)	V	-	
Length (Normal Pool)	L	-	
Maximum Depth (Normal Pool)	Z_m	-	
Outlet Elevation	Z_C	-	
Normal Pool Elevation	Z_n	-	
Spillway Elevation	Z_s	-	
Shoreline Length	L_s	-	
Morphometric/Hydrologic (Calculated)			
Mean Depth	$\overline{Z}$	V/A	
Development of Volume	Z/Z_m	-	
Mean Breadth	$\bar{b}$	A/L	110
Drainage Area/Surface Area Ratio	DA/SA	-	

(Continued)

(Sheet 2 of 4)

Table 2-2 (Continued)

Characteristics	Symbol	Formulation	Reference No.
Morphometric/Hydrologic (Calculated) (Cont.)			
Shoreline Development Ratio	D_L	$\frac{L_s}{2\sqrt{\pi A}}$	110
Mean Hypolimnion Depth	Z_H	$Z(1 - Z_T/Z_m)$	107
Relative Depth	Z_r	$\frac{50\ Z_m \sqrt{\pi}}{\sqrt{A}}$	110
Hydraulic Residence Time	τ	V/Q	
Flushing Rate	α	$1/\tau$	32
Single Storm Flushing Rate	β	Q_s/V	32
Areal Water Load	q_s	Q/A	
Densimetric Froude Number	F_d	$320 * \frac{LQ}{ZV}$	32
Plunge Point Depth	D_p	$\left(\frac{1}{F_p}\right)^{1/3}\left[Q^2/\left(W^2 \cdot g \cdot \frac{\Delta\rho}{\rho}\right)\right]^{1/3}$	67

(Continued)

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Table 2-2 (Concluded)

Characteristics	Symbol	Formulation	Reference No.
Chemical			
Dissolved Oxygen Saturation	DO_{sat}	$DO_{sat} = \exp(7.7117 - 1.31403 * \ln(T + 45.93) + 5.25 * \ln(1 - h/44.3))$	89
Oxygen Supply	T_{DO}	$T_{DO} = DO_i * Z_H/\Delta HOD$	107
Un-ionized Ammonia	NH_3^{UI}	$NH_3^{UI} = \left[1 + 1/\ln^{-1}(0.09019 + 2,729.92/T_d - pH_d) * C_e^T Q_e + C_u^T Q_u /Q_e + Q_e\right]$	112
Nitrogen Supersaturation Potential	N_f	See ETL 1110-2-239	
Total Dissolved Solids	TDS	TDS ≈ -0.6 * Specific Conductance	
Soluble Reactive Phosphorus	SRP	SRP ~ (0.4 to 0.5) * TP	34

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(2) Reservoirs with high shoreline development ratios are indicative of dendritic systems with many coves and embayments, while low values of the ratio are often indicative of more prismatic type reservoirs. Biological productivity usually is higher in coves than in the main pool; thus, reservoirs having high shoreline development ratios tend to be more productive.

(3) Fetch is the distance over water that the wind has blown uninterrupted by land. When computed along the direction of the prevailing wind, the fetch length can provide an indication of wave heights and potential erosion areas on the windward reservoir side where the waves will break.

(4) The shape of area-capacity curves integrates morphometric parameters that relate to biological productivity. Reservoirs with flatter slopes on the area-elevation, elevation-volume curves usually have higher productivity.

c. Longitudinal Gradients. Reservoirs can exhibit pronounced longitudinal and vertical physical, chemical, and biological gradients. Long, dendritic reservoirs, with tributary inflows located a considerable distance from the outflow and unidirectional flow from headwater to dam, develop gradients in space and time. Although these gradients are continuous from headwater to dam, three characteristic zones result: a riverine zone, a zone of transition, and a lacustrine zone (Figure 2-1).

(1) Riverine zone. The riverine zone is relatively narrow, well mixed, and although water current velocities are decreasing, advective forces are still sufficient to transport significant quantities of suspended particles, such as silts, clays, and organic particulates. Light penetration in this zone is minimal and may be the limiting factor that controls primary productivity in the water column. The decomposition of tributary organic loadings often creates a significant oxygen demand, but an aerobic environment is maintained because the riverine zone is generally shallow and well mixed. Longitudinal dispersion may be an important process in this zone.

(2) Zone of transition. Significant sedimentation occurs through the transition zone, with a subsequent increase in light penetration. Light penetration may increase gradually or abruptly, depending on the flow regime. At some point within the mixed layer of the zone of transition, a compensation point between the production and decomposition of organic matter should be reached. Beyond this point, production of organic matter within the reservoir mixed layer should begin to dominate (Figure 2-1).

(3) Lacustrine zone. The lacustrine zone is characteristic of a lake system (Figure 2-1). Sedimentation of inorganic particulates is low; light penetration is sufficient to promote primary production, with nutrient levels the limiting factor; and production of organic matter exceeds decomposition within the mixed layer. Entrainment of metalimnetic and hypolimnetic water, particulates, and nutrients may occur through internal waves or wind mixing during the passage of large weather fronts. Hypolimnetic mixing may be more extensive in reservoirs than lakes because of bottom withdrawal. Bottom

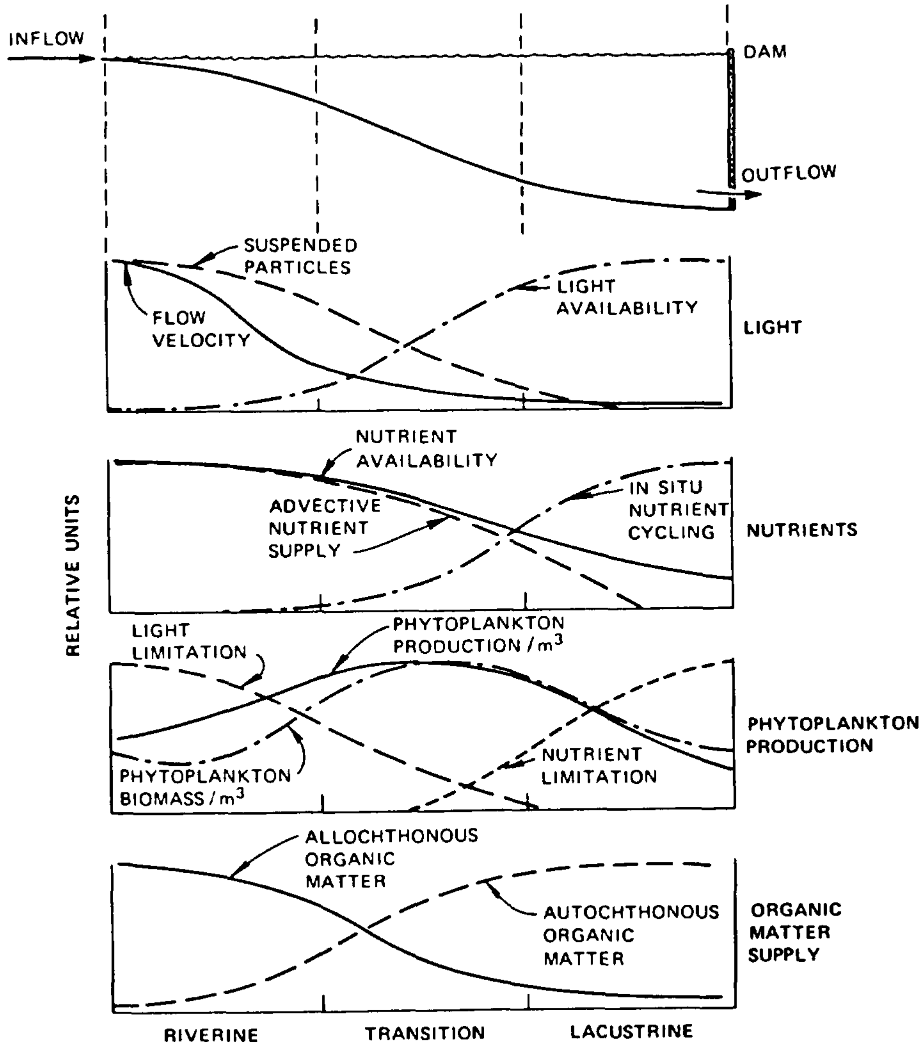

Figure 2-1. Longitudinal patterns in reservoir water quality (after Item y, Appendix B)

withdrawal removes hypolimnetic water and nutrients and may promote movement of interflows or underflows into the hypolimnion. In addition, an intake structure may simultaneously remove water from the hypolimnion and metalimnion.

d. Vertical Gradients. Attaining reservoir water quality objectives can be significantly affected by vertical stratification in the reservoir. This stratification typically occurs through the interaction of wind and solar isolation at the reservoir surface and creates density gradients that can influence reservoir water quality (see Figure 2-2). Stratification also can result from density inflows (see para 2-7i) or high total dissolved solids (TDS) or

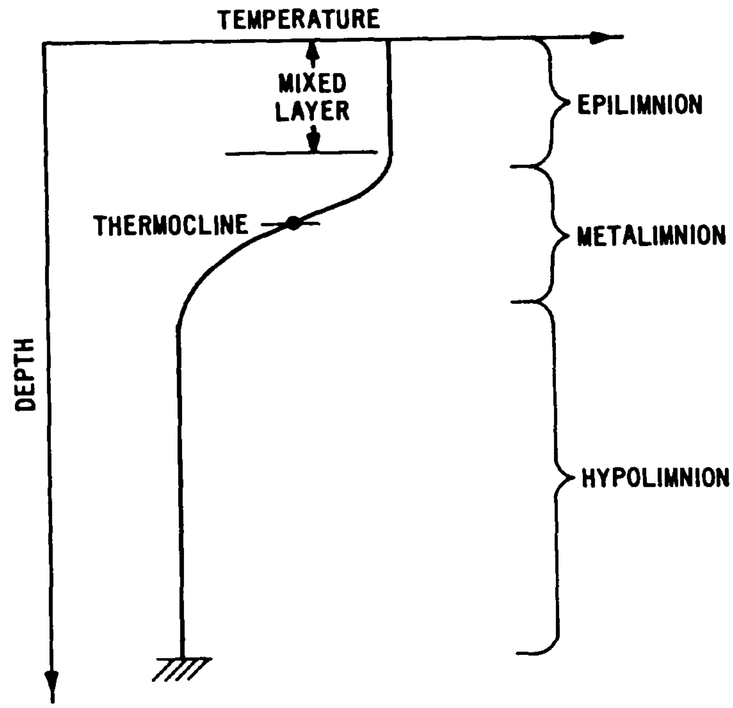

Figure 2-2. Vertical zonation resulting from thermal stratification

suspended solids (SS) concentrations. Because of density stratification and its sensitivity to meteorological conditions and tributary inflows, proper hydraulic outlet design is imperative to ensure that reservoir and release water quality objectives can be met. Reservoir hydraulic outlet designs include the capability for bottom, surface, and multilevel withdrawal; low-flow releases; or the passing of large flows over a spillway.

(1) Bottom withdrawal. Bottom withdrawal structures are located near the deepest part of a reservoir (Figure 2-3). Historically, bottom withdrawal structures have been the most common outlet structures used to release reservoir waters. They release cold waters from the deep portion of the reservoir; however, these waters may be anoxic during periods of stratification. Bottom outlets can release density interflows or underflows (e.g., flow laden with sediment or dissolved solids) through the reservoir and generally provide little or no direct control over release water quality. In order to control release water quality in projects with bottom outlets, external techniques such as release aeration, hypolimnetic aeration, or localized mixing must be used.

(2) Surface withdrawal. Surface withdrawal structures release waters from near the surface of the reservoir pool (Figure 2-4) and include morning

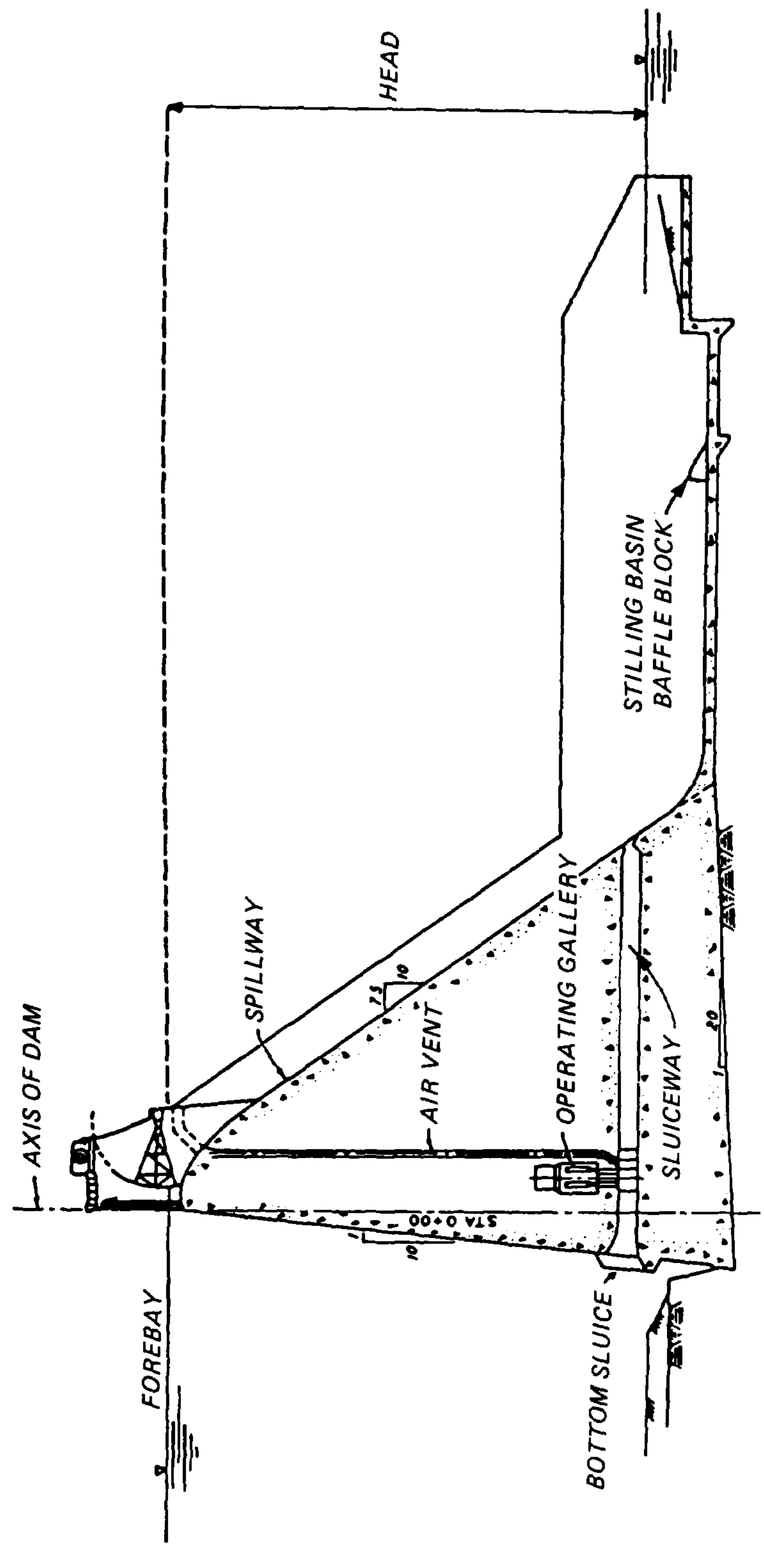

Figure 2-3. Illustration of bottom withdrawal structure, spillway, and stilling basin

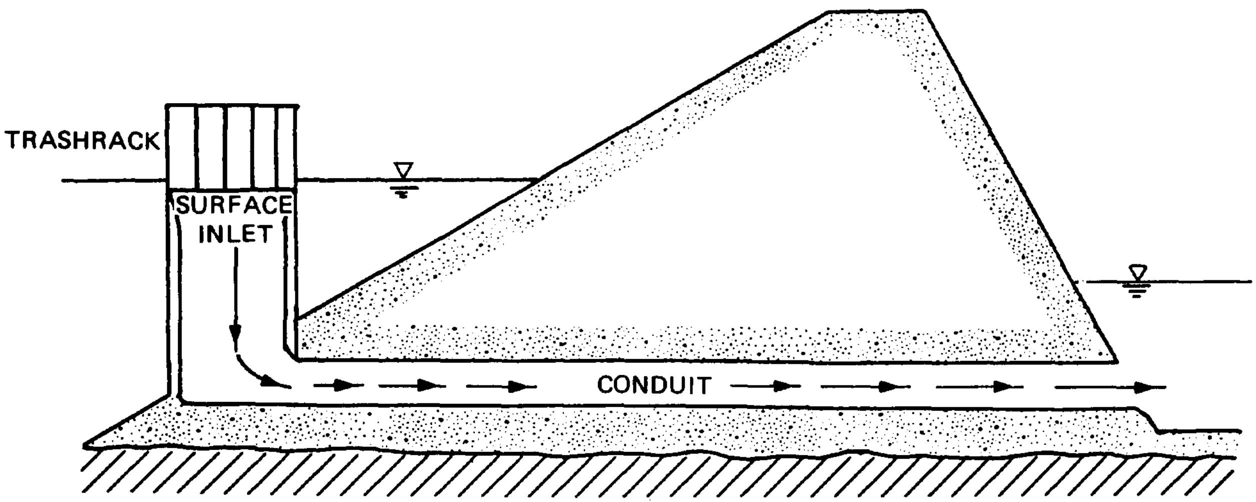

Figure 2-4. Example of surface withdrawal structure

glory, drop inlet siphon, or shaft inlets. Outlet structures at the surface generally release relatively warm, well-oxygenated waters. Surface outlets must be designed to operate within the range of fluctuation of the reservoir water surface. The surface outlet becomes unusable once the reservoir water surface elevation falls below the crest of a surface outlet structure. Density interflows or underflows cannot be released using surface outlets, nor is there any direct control over the water quality of the release using the outlet structure. Few external techniques for controlling water quality within the reservoir can be used to control the water quality of releases from surface structures.

(3) Multilevel withdrawal. Multilevel withdrawal structures have one or more outlet towers, each containing a number of inlet ports at different elevations (Figure 2-5). This configuration provides the flexibility to release water from several levels within the reservoir. Designing port locations at various elevations may permit reservoir operation to meet release water quality objectives by withdrawing water with the desired quality from appropriate elevations in the reservoir. However, in a single tower, only one port can be effectively operated at any time if the reservoir is stratified. Operating two ports at different elevations simultaneously in a stratified reservoir with a single wet well can result in density blockage of flow, flow instability, pulsating release quality, and overall reduced control over release quality. As a result, a single wet well is not conducive to blending water from different elevations. However, with a system of two or more wet wells, one port in each wet well can be opened to blend waters from different elevations to meet downstream water quality objectives. Multilevel outlets can also be used to pass density flows through reservoirs, but port capacities are generally limited to those capacities used in normal operation. Also, larger

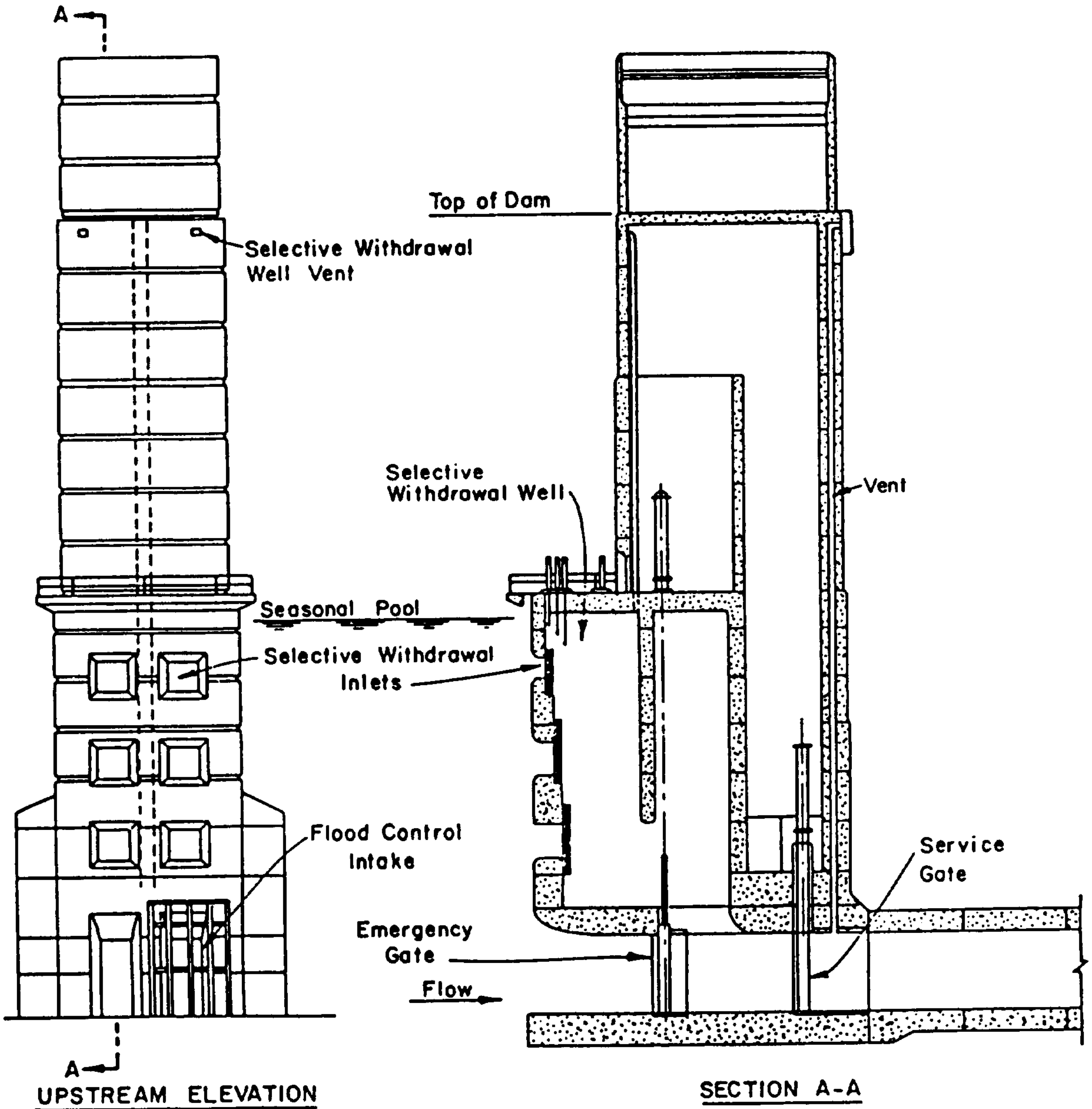

Figure 2-5. Dual wet well multilevel withdrawal structure

flows can be passed by combining a flood control outlet or spillway with the multilevel intake structure. However, using spillway releases and hydropower releases may not result in a uniform downstream quality. Such waters may not readily mix because of density differences. The flood control outlet is commonly a large-capacity bottom outlet. Flood control operation, however, generally results in temporary loss of control over release quality unless nonflood flows also are discharged through the bottom outlet or over the spillway.

e. Water Budget.

(1) The water balance in reservoirs is the result of the income of and losses from the reservoir and can have a significant effect on reservoir and release water quality on an annual, seasonal, daily, and even hourly basis. The income may consist of precipitation on the water surface, tributary inflow, watershed runoff, point source discharges, and ground water. Water losses occur through evaporation from the water surface, evapotranspiration by aquatic plants, reservoir withdrawals, leakage, and ground-water recharge or seepage. The change in water storage is a function of the difference between income and loss.

(2) The total water budget varies from wet year to dry, season to season, and day to day. Any assessment of water quality requires a clear understanding of the project's water budget and the variability of that budget with time. Factors such as chemical concentrations and stratification, turbidity, productivity, thermal regime, and sediment transport are strongly influenced by a project's water budget.

f. Water Properties. Water has several unique physical properties that must be considered in water quality assessment. These properties include density, specific heat, viscosity, and surface tension.

(1) Density. Water has its maximum density, 1 gram per milliliter, near 4° C (Figure 2-6) and is a nonlinear function of temperature. Water becomes less dense or buoyant as the temperature either increases or decreases from 4° C. Ice floats on water, and warmer water floats on cold water because of these density differences. Further, the temperature-density relation is nonlinear; the density difference between 20° and 21° C is approximately equal to the density difference between 5° and 10° C. Density is also significantly influenced by TDS and SS concentrations. Normally, as TDS and SS concentrations increase, so does density. Density differences influence internal reservoir mixing processes, as well as water quality.

(2) Specific heat. The specific heat of water is 1.0 kilocalorie per kilogram °C, which is four times the specific heat of air. As a result, water gains or loses heat more slowly than air. Therefore, large changes in daily air temperatures generally elicit much smaller changes in water temperature. The large reservoir water mass and high specific heat of the water

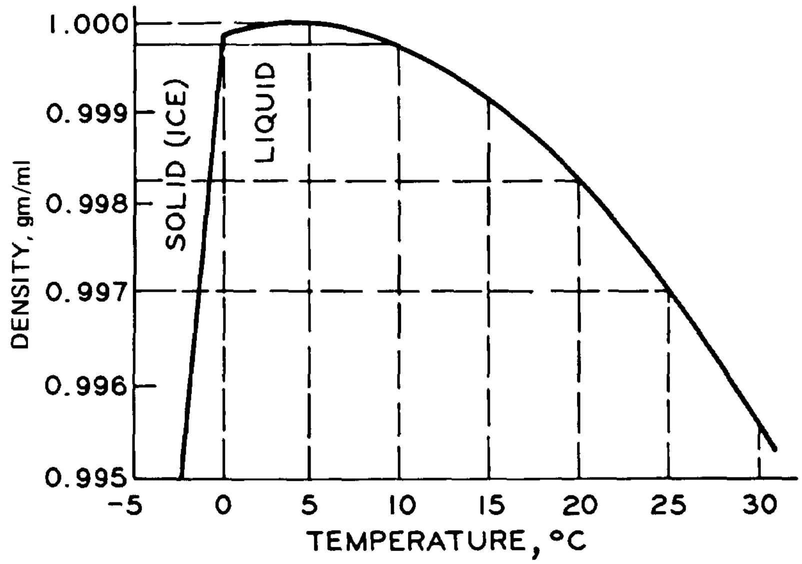

Figure 2-6. Water density as a function of temperature

cause temperatures in reservoirs to increase more slowly in the spring and decrease more slowly in the fall than stream or air temperatures.

(3) Viscosity. Viscosity is the internal fluid resistance, caused by molecular attraction, that makes a fluid resistant to flow and is a function of temperature, decreasing as temperature increases. An illustration of this property is that particulate matter, suspended in the water (i.e., algae, detritus, sediment), will settle faster as temperature increases, since viscosity is lower at higher temperatures.

(4) Surface tension. Surface tension at the air/water interface is caused by unbalanced molecular attractions that exert an inward adhesion to the liquid phase (Ref. 110). Surface tension decreases with increasing temperature. Also, surface tension can maintain the concentration of debris on the surface and form a unique microhabitat for microorganisms. Organic compounds, either naturally produced dissolved organic carbon (DOC) or organic pollutants such as oil, markedly reduce surface tension.

g. Thermal regime. The annual temperature distribution represents one of the most important limnological processes occurring within a reservoir. Thermal variation in a reservoir results in temperature-induced density stratification, and an understanding of the thermal regime is essential to water quality assessment. A brief discussion of the thermal regime of a reservoir in the temperate climate is presented in the following paragraphs.

(1) Spring thermal regime. As the ice cover deteriorates in the spring, the surface water, which is near 0° C, begins to warm and approach the temperature of the bottom water. Since the density of the surface water increases

as it approaches 4° C, this surface water sinks and mixes with the water below it. During this period, there is relatively little thermally induced resistance to mixing because of the small density differences, and the reservoir becomes uniform near 4° C. This period of uniform temperature is referred to as spring turnover. The extent of this period is primarily dependent on inflow density, wind mixing, and solar insolation. Solar insolation warms the surface water and thereby establishes a density gradient between the surface and underlying water. However, wind energy introduced across the water surface stirs the water column and distributes this heat into the water column, resulting in an increase in the temperature of the entire water column to or above 4° C. As solar insolation intensifies, wind energy no longer can overcome the density gradient between the surface and bottom and completely mix the water column. As a result, a temperature gradient is established in the water column, which is called thermal stratification.

(2) Summer thermal regime. During the summer, solar insolation has its highest intensity and the reservoir becomes stratified into three zones (Figure 2-2).

(a) Epilimnion or mixed layer. This upper zone represents the less dense, warmer water in the reservoir. It is fairly turbulent since its thickness is determined by the turbulent kinetic energy (TKE) inputs (wind, convection, etc.), and a relatively uniform temperature distribution throughout this zone is maintained.

(b) Metalimnion. The metalimnion is the middle zone that represents the transition from warm surface water to cooler bottom water. There is a distinct temperature gradient through the metalimnion. The metalimnion in some references is called the thermocline. The thermocline, however, represents the plane or surface of maximum rate of change of temperature in the metalimnion.

(c) Hypolimnion. The hypolimnion is the bottom zone of colder water that is relatively quiescent in lakes. Bottom withdrawal or fluctuating water levels in reservoirs, however, may significantly increase hypolimnetic mixing.

(3) Fall thermal regime. As solar insolation decreases during autumn and the air and inflow temperatures cool, reservoir heat losses exceed heat inputs, and water surface temperatures decrease (Figure 2-7). This results in the surface water becoming denser and mixing with deeper water through wind and convection currents, and a reduction of the density difference between the mixed layer and hypolimnion. This situation results in a deepening of the mixed layer and erosion of the metalimnion. As fall cooling progresses, the water column eventually reaches a uniform temperature. This period of uniform temperature in the water column is called fall turnover.

(4) Winter thermal regime. Thermal uniformity of the water column will continue unless the surface water freezes. Ice formation prevents wind mixing, and inverse stratification may form under the ice. The bottom water

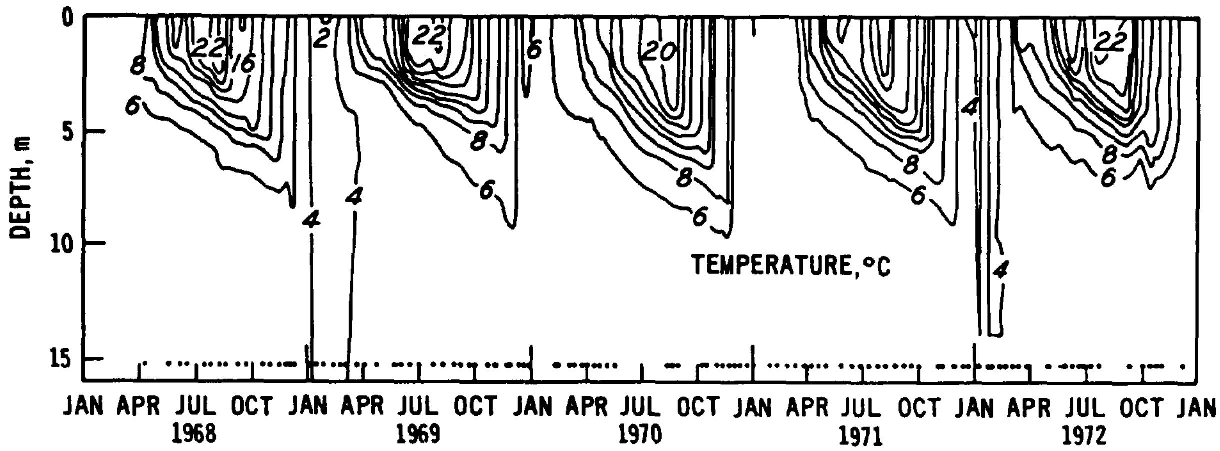

Figure 2-7. Recurring annual stratification pattern for temperate reservoir

or deeper strata may stay near maximum density at 4° C, but the surface waters become colder and less dense and offer resistance to mixing, so an inverse stratification occurs with 0° C water at the surface and 4° C water near the bottom (Figure 2-7).

(5) Exceptions. The above discussion of thermal regimes in reservoirs (paras 2-7g(1)-(4)) is generally applicable, but, as in most phenomena, there are exceptions. One exception is that, although spring and fall turnover usually produce uniform temperature in the vertical, the influence of dissolved and/or suspended constituents can result in the existence of a chemically induced density gradient, particularly in deeper reservoirs. Another exception is that certain inflow and withdrawal conditions, such as bottom withdrawals that deplete the hypolimnion, can greatly alter the density gradient within the pool. As a result, specific characteristics of each reservoir must be considered in any water quality assessment.

h. Other Stratification. Density stratification due to a temperature gradient is the most common type of stratification, but other factors may also produce density differences that result in reservoir stratification. If density differences prevent mixing with the overlying water, the resulting condition is called a meromictic or incompletely mixed system. In meromictic reservoirs, the bottom waters are isolated by a monimolimnion, which is similar to the metalimnion. Density differences may be due to physical, chemical, or biological factors.

(1) Physical. High suspended sediment concentrations may increase fluid densities and provide resistance to mixing. Although suspended solids settle rapidly, fine colloidal particles transported into a reservoir during major storm events can prevent the bottom waters from mixing with the overlying water column until settling, dilution, and entrainment eliminate this condition.

As a consequence, a difference in density between the bottom and overlying water can occur for a period after a major storm event.

(2) Chemical. High TDS or salinity concentrations can increase water density and prevent complete mixing of the system. The gradient between the upper mixed layer and lower dense chemical layer is a chemocline.

(3) Biological. Decomposition of sediments or sedimenting organic matter can result in salt accumulation that increases the density of the bottom waters and prevents mixing. This condition, called biogenic meromixis, may occur during the initial filling and transition period of a reservoir when decomposition of flooded soils and vegetation is intense. However, this type of stratification generally decreases through time.

i. Inflow Mixing Processes. When tributary inflow enters a reservoir, it displaces the reservoir water. If there is no density difference between the inflow and reservoir waters, the inflow will mix with the reservoir water as the inflow parcel of water moves toward the dam. However, if there are density differences between the inflow and reservoir waters, the inflow moves as a density current in the form of overflows, interflows, or underflows (Figure 2-8). Knapp (Ref. 85) provides an excellent qualitative discussion of inflow mixing, while Ford and Johnson (Ref. 12) discuss reservoir density currents and inflow processes.

j. Internal Mixing. Internal mixing is the term used to describe mixing within a reservoir from such factors as wind, Langmuir circulation, convection, Kelvin-Helmholtz instabilities, and outflow (Figure 2-9). Additional

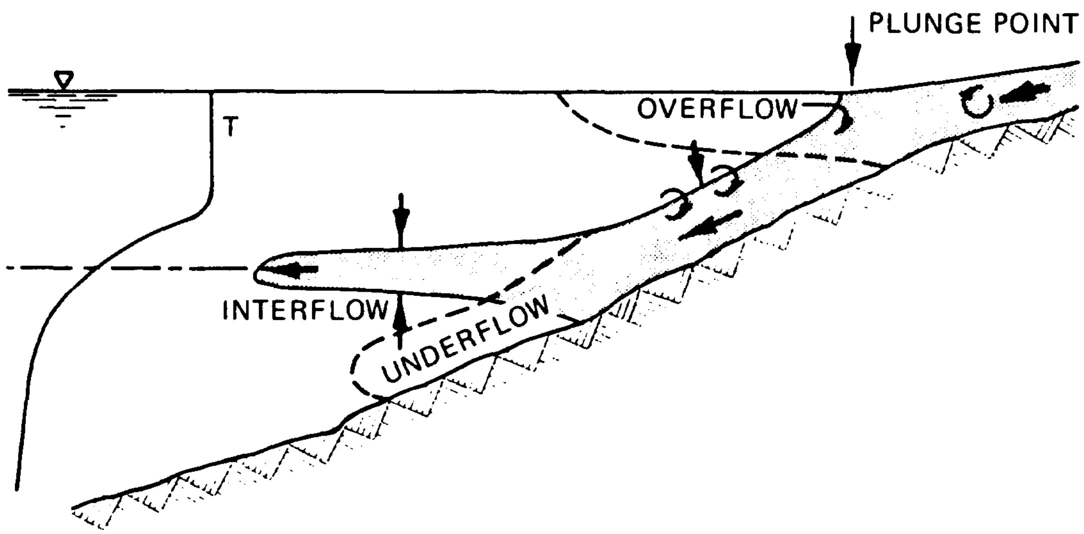

Figure 2-8. Density inflows to reservoirs (after Ref. 12)

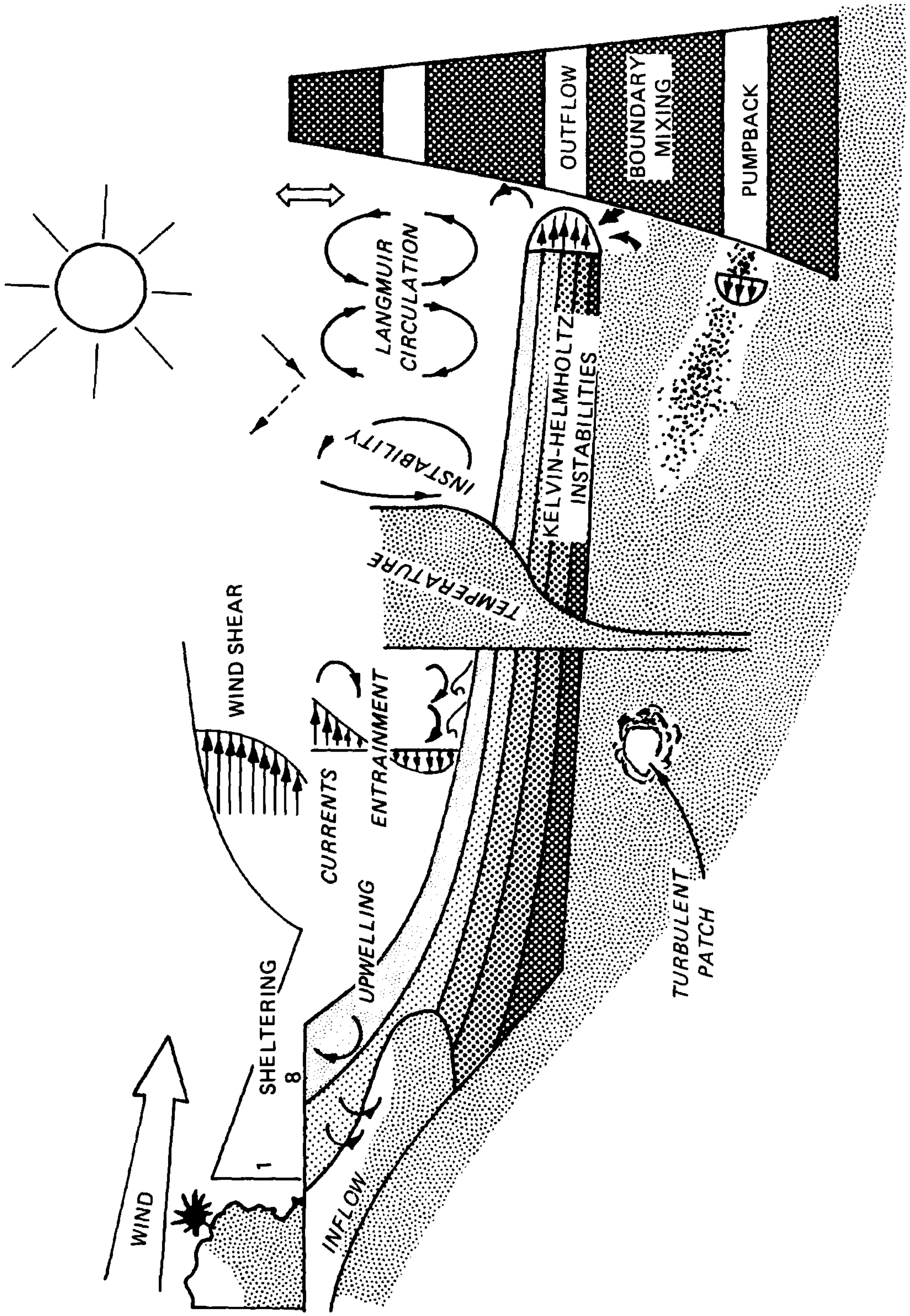

Figure 2-9. Internal mixing processes in reservoirs

topical information is available from the following sources: dynamics of large lakes (Refs. 55 and 89 and Item h); mixing dynamics (Refs. 11, 66, 73, and 81); turbulence (Ref. 103); inflow dynamics (Ref. 12); and outflow dynamics and selective withdrawal (Ref. 80). An excellent reference on the influence of density stratification on mixing and flow is the Proceedings of the Second International Symposium on Stratified Flow (Ref. 57).

(1) Wind mixing. In many lakes and reservoirs, wind is a major energy source for mixing. Mixing results from the interaction and cumulative effects of wind-induced shear at the air/water interface (e.g., currents, surface waves, internal waves, seiches, and entrainment). Wind is highly variable, with seasonal, synoptic, and diel (24-hour) cycles. Synoptic cycles correspond to the passage of major weather systems or fronts and have a period of 5 to 7 days. Wind is an important factor influencing the depth of the mixed layer. Langmuir circulations are wind-induced surface currents that move as vertical helices. Wind energy is converted into turbulence by many different processes, including the direct production of turbulence. This surface turbulence is transported downward and mixes water until the density gradient or thermal resistance to mixing dissipates the energy, resulting in the mixed layer depth.

(2) Convection. Convective mixing results from density instabilities due to cooling of surface waters. As the surface water cools it becomes more dense and settles, mixing with underlying strata. Penetrative convective cooling during the fall can be an important factor in deepening of the mixed layer and erosion of the metalimnion (Figure 2-10).

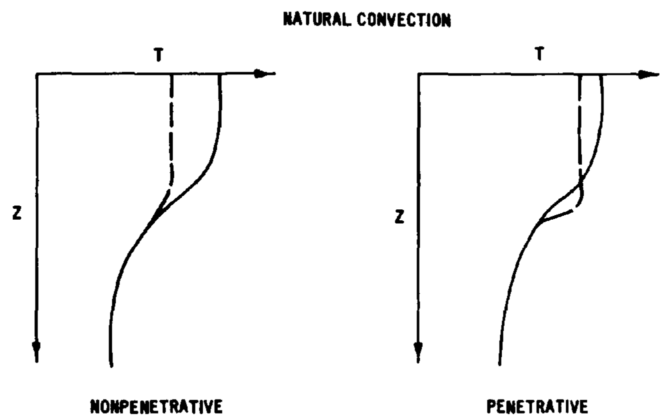

Figure 2-10. Influence of penetrative convective mixing on deepening the mixed layer

(3) Kelvin-Helmholtz instabilities. Internal and surface waves and seiches transport momentum but contribute little mixing unless energy is dissipated through shear or friction. When internal waves become unstable and break, the process is referred to as a Kelvin-Helmholtz instability, and mixing occurs at the interface. Since reservoir operation can result in

fluctuating water levels and unsteady flow, significant mixing can occur at various interfaces in the reservoir such as the sediment/hypolimnion interface, meta/hypolimnion, and epi/metalimnion interface.

(4) Outflow mixing. When water is released from a reservoir, potential energy is converted into kinetic energy. Mixing is a result of this conversion of energy, although restricted to the zone of outflow, and is proportional to the third power of the discharge. The outflow zone is a function of the stratification regime and the hydraulic outlet geometry and operation (Refs. 7, 22). Hypolimnetic or bottom withdrawal can increase mixing in the hypolimnion and alter the stratification profile in the pool. Hydroelectric power generation can significantly increase mixing in the pool.

k. Pumped Storage. Pumped-storage hydroelectric power operations can increase mixing both through outflow mixing and through mixing and entrainment of the pumpback jet into the reservoir. Depending on the elevation of the inlets, the pumpback jet may move as a density flow entraining the surrounding water until it reaches a level with comparable density (Figure 2-11). This mixing can result in the vertical movement of hypolimnetic constituents into the upper waters.

l. Sediment Dynamics. Sediment deposition patterns and sediment quality, however, markedly influence reservoir water quality. Sediment characterization, yield, transport mechanics, and other aspects of sedimentation engineering (Ref. 106) are important considerations.

m. Deposition Patterns. Gravels, sands, and other coarse sediments are deposited in the reservoir delta and do not influence water quality. The reservoir delta is defined as the deposition zone between the maximum normal flood pool and the normal conservation pool. Suspended sediment transported into the reservoir typically ranges from coarse silts and particulate organic matter to fine clays and colloidal organic matter. As turbulence and river velocities decrease in the reservoir headwater, the sediment-carrying capacity of the river decreases and sediments are deposited. Since the river and its constituent load generally follow the old thalweg through the reservoir, sediment deposition initially is greatest in the old channel. Sedimentation and deposition rates are highest in the headwater and decrease exponentially down the reservoir with plug flow characteristics. This results in a longitudinal sorting of particulate matter by particle size. The coarse silts and organic particles settle in the upper portion of the reservoir; fine silts, coarse clays, and finer organic particles settle next, with the fine clays and colloidal material settling very slowly. Finally, sediment deposition patterns are extremely complex and reflect the interaction of inflow patterns and storage patterns as well as physical, chemical, biological, and seasonal factors that affect the water and the watershed. An example of a typical distribution of deposited particle size in a reservoir is:

a. Initial conditions, typical density stratification

b. Buoyant jetting inflow

c. Shortly after inflow ceases

d. Long time after inflow ceases

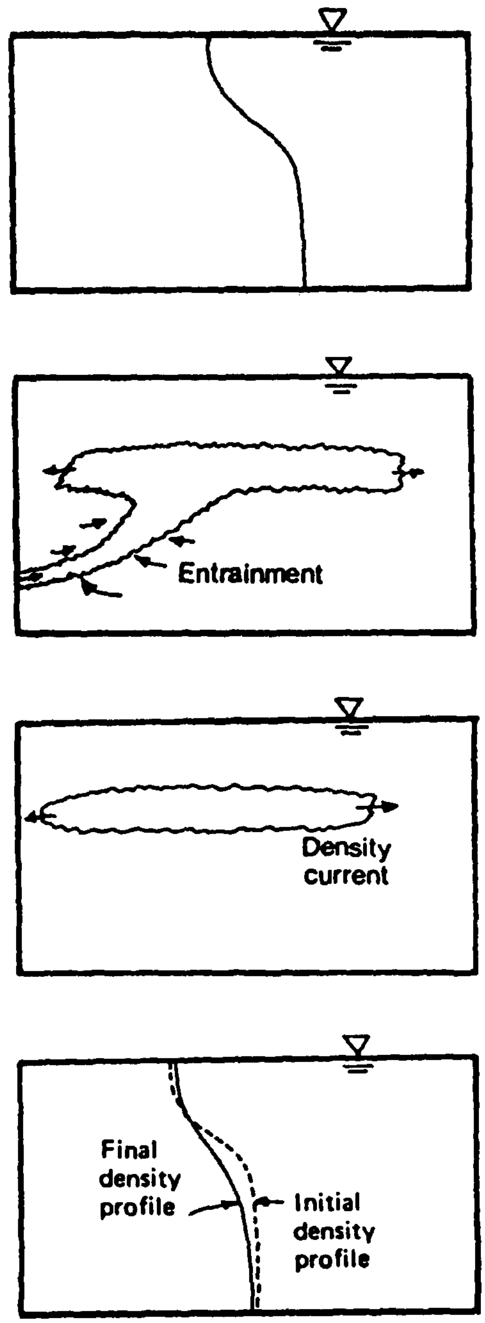

Figure 2-11. Important hydrodynamic features of pumped-storage reservoirs subject to jetting inflows (after Ref. 21)

Particle Size	Percent of Deposited Sediment Inlet	Mid-Reservoir	Outlet
Sand	5	<1	0
Silt	76	61	51
Clay	19	38	49

n. Quality. Water quality characteristics of the sediment are reflected by the particle size distribution. Coarse organic matter and debris generally settle in the delta with the gravels and coarse sands. River plankton or algae are generally thick-walled species or diatoms that can withstand abrasion during transport in the river but settle rapidly in a lower energy regime. These algae and similar particulate organic matter in the coarse silt size range typically settle in the upper portion of the reservoir. Finer particulate organic matter settles farther downstream in the reservoir, with the colloidal organic matter settling even more slowly. In general, the smaller the particle size, the greater the surface area to volume ratio and the greater the sorptive capacity for transporting adsorbed phosphorus, organic carbon, metals, and contaminants. Clays have a high sorptive capacity while sand has essentially no sorptive capacity. As a result, nutrients, metals, and contaminants may be transported into or through the reservoir adsorbed to the fine silts and clays. Since there is a longitudinal sorting by median particle size diameter, there may also be longitudinal gradients of water quality constituents associated with the sediment.

2-8. Chemical Characteristics of Reservoir Processes.

a. Constituents. Some of the most important chemical constituents in reservoir waters that affect water quality are needed by aquatic organisms for survival. These include oxygen, carbon, nitrogen, and phosphorus. Other important constituents are silica, manganese, iron, and sulfur.

(1) Dissolved oxygen. Oxygen is a fundamental chemical constituent of water bodies that is essential to the survival of aquatic organisms and is one of the most important indicators of reservoir water quality conditions. The distribution of dissolved oxygen (DO) in reservoirs is a result of dynamic transfer processes from the atmospheric and photosynthetic sources to consumptive uses by the aquatic biota. The resulting distribution of DO in the reservoir water strongly affects the solubility of many inorganic chemical constituents. Often, water quality control or management approaches are formulated to maintain an aerobic or oxic (i.e., oxygen-containing) environment. Oxygen is produced by aquatic plants (plankton and macrophytes) and is consumed by aquatic plants, other biological organisms, and chemical oxidations. In reservoirs, the DO demand may be divided into two separate but highly interactive fractions: sediment oxygen demand (SOD) and water column demand.

(a) Sediment oxygen demand. The SOD is typically highest in the upstream area of the reservoir just below the headwater. This is an area of transition from riverine to lake characteristics. It is relatively shallow but does stratify. The loading and sedimentation of organic matter is high in this transition area and, during stratification, the hypolimnetic DO to satisfy this demand can be depleted. If anoxic conditions develop, they generally do so in this area of the reservoir and progressively move toward the dam during the stratification period. The SOD is relatively independent of DO when DO concentrations in the water column are greater than 3 to 4 milligrams per liter but becomes limited by the rate of oxygen supply to the sediments.

(b) Water column demand. A characteristic of many reservoirs is a metalimnetic minimum in DO concentrations or negative heterograde oxygen curve (Figure 2-12). Density interflows not only transport oxygen-demanding material into the metalimnion but can also entrain reduced chemicals from the

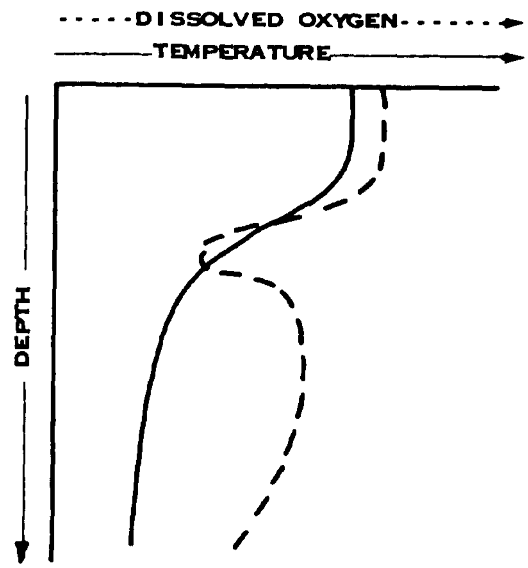

Figure 2-12. Characteristic metalimnetic DO minimum

upstream anoxic area and create additional oxygen demand. Organic matter and organisms from the mixed layer settle at slower rates in the metalimnion because of increased viscosity due to lower temperatures. Since this labile organic matter remains in the metalimnion for a longer time period, decomposition occurs over a longer time, exerting a high oxygen demand. Metalimnetic oxygen depletion is an important process in deep reservoirs. A hypolimnetic oxygen demand generally starts at the sediment/water interface unless underflows contribute organic matter that exerts a significant oxygen demand. In addition to metalimnetic DO depletion, hypolimnetic DO depletion also is important in shallow, stratified reservoirs since there is a smaller hypolimnetic volume of oxygen to satisfy oxygen demands than in deep reservoirs.

(c) Dissolved oxygen distribution. Two basic types of vertical oxygen distribution may occur in the water column: an orthograde and clinograde oxygen distribution (Figure 2-13). In the orthograde distribution, oxygen concentration is a function primarily of temperature, since oxygen consumption is limited. The clinograde oxygen profile is more representative of Corps reservoirs where the hypolimnetic oxygen concentration progressively decreases during stratification (Figure 2-13) and can occur during both summer and winter stratification periods.

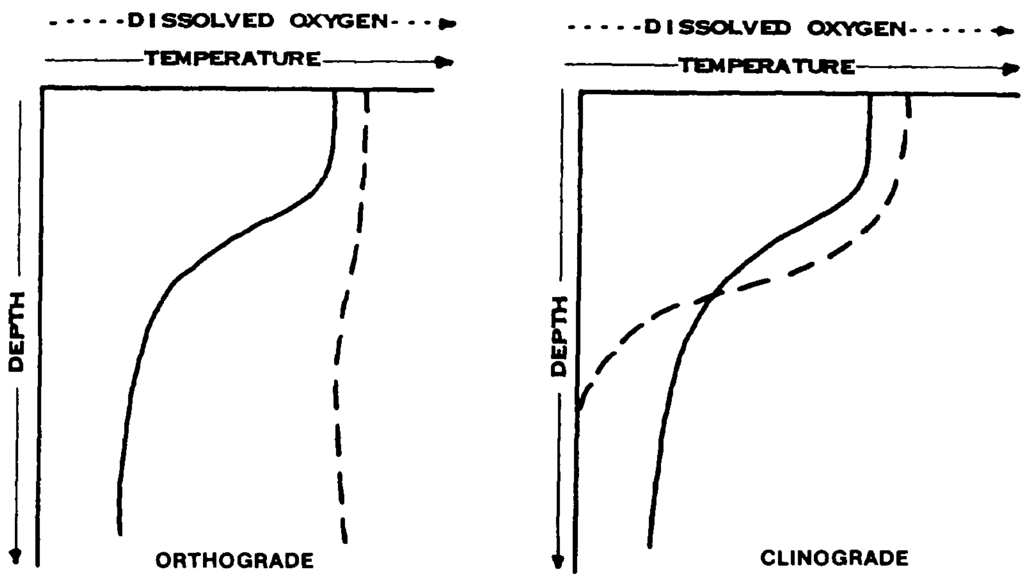

Figure 2-13. Orthograde and clinograde vertical DO distributions

(2) Inorganic carbon. Inorganic carbon represents the basic building block for the production of organic matter by plants. Inorganic carbon can also regulate the pH and buffering capacity or alkalinity of aquatic systems. Inorganic carbon exists in a dynamic equilibrium in three major forms: carbon dioxide (CO_2), biocarbonate ions (HCO_3^-), and carbonate ions ($CO_3^=$). Carbon dioxide is readily soluble in water and some CO_2 remains in a gaseous form, but the majority of the CO_2 forms carbonic acid which dissociates rapidly into HCO_3^- and $CO_3^=$ ions. This dissociation results in a weakly alkaline system (i.e., pH ~ 7.1 or 7.2). There is an inverse relation between pH and CO_2. When aquatic plants (plankton or macrophytes) remove CO_2 from the water to form organic matter through photosynthesis, the pH increases. The extent of this pH change provides an indication of the buffering capacity of the system. Weakly buffered systems with low alkalinities (i.e., <500 microequivalents per

liter) experience larger shifts in pH than well-buffered systems (i.e., >1,000 microequivalents per liter).

(3) Nitrogen. Nitrogen is important in the formulation of plant and animal protein. Nitrogen, similar to carbon, also has a gaseous form. Many species of blue-green algae can use or fix elemental or gaseous N_2 as a nitrogen source. The most common forms of nitrogen in aquatic systems are ammonia (NH_3-N), nitrite (NO_2-N), and nitrate (NO_3-N). All three forms are transported in water in a dissolved phase. Ammonia results primarily from the decomposition of organic matter. Nitrite is primarily an intermediate compound in the oxidation or nitrification of ammonia to nitrate, while nitrate is the stable oxidation state of nitrogen and represents the other primary inorganic nitrogen form besides NH_3 used by aquatic plants.

(4) Phosphorus. Phosphorus is used by both plants and animals to form enzymes and vitamins and to store energy in organic matter. Phosphorus has received considerable attention as the nutrient controlling algal production and densities and associated water quality problems. The reasons for this emphasis are: phosphorus tends to limit plant growth more than the other major nutrients (see Table 2-3); phosphorus does not have a gaseous phase and ultimately originates from the weathering of rocks; removal of phosphorus from point sources can reduce the growth of aquatic plants; and the technology for removing phosphorus is more advanced and less expensive than nitrogen removal.

TABLE 2-3

Nutrient Demand:Supply Ratios During Nonproductive and Productive Seasons[1]

Element	Demand:Supply (range)	
	Late Winter	Midsummer
Phosphorus	80,000	800,000
Nitrogen	30,000	300,000
Carbon	5,000	6,000
Iron, silicon	Generally low, but variable	
All other elements	Less than 1,000	

[1]After Item ss, Appendix B.

Phosphorus is generally expressed in terms of the chemical procedures used for measurement: total phosphorus, particulate phosphorus, dissolved or filterable phosphorus, and soluble reactive phosphorus (SRP). Phosphorus is a very reactive element; it reacts with many cations such as iron and calcium and is readily sorbed on particulate matter such as clays, carbonates, and inorganic colloids. Since phosphorus exists in a particulate phase, sedimentation represents a continuous loss from the water column to the sediment. Sediment phosphorus, then, may exhibit longitudinal gradients in reservoirs similar to sediment silt/clay gradients. Phosphorus contributions from sediment under anoxic conditions and macrophyte decomposition are considered internal phosphorus sources or loads, are in a chemical form available for plankton uptake and use, and can represent a major portion of the phosphorus budget.

(5) Silica. Silica is an essential component of diatom frustules or cell walls. Silica uptake by diatoms can markedly reduce silica concentrations in the epilimnion and initiate a seasonal succession of diatom species (Ref. 110). When silica concentrations decrease below 0.5 milligram per liter, diatoms generally are no longer competitive with other plankton species.

(6) Other nutrients. Iron, manganese, and sulfur concentrations generally are adequate to satisfy plant nutrient requirements. Oxidized iron (III) and manganese (IV) are quite insoluble in water and occur in low concentrations under aerobic conditions. Under aerobic conditions, sulfur usually is present as sulfate.

b. Gas Exchange.

(1) Gas exchange across the air/water interface is a function of atmospheric pressure, temperature, concentration gradients, and turbulence. The solubility of most gases in water is directly proportional to the partial pressure in the gaseous phase (Henry's Law) and decreases in a nonlinear manner with increasing temperature and altitude (i.e., decreasing atmospheric pressure). Gas transfer is directly proportional to the concentration gradient and turbulence at the air/water interface; however, molecular diffusion is an insignificant mechanism for gas exchange.

(2) Gas exchange across the air/water interface occurs for several gases other than oxygen. Nitrogen, both as elemental nitrogen and ammonia-N, and carbon dioxide also diffuse in and out of the water across this interface. Methane and hydrogen sulfide are two gases that are occasionally produced in the reservoir and may be released across the air/water interface. Water also can, on occasion, become supersaturated with gases. Release of supersaturated gaseous nitrogen, methane, and hydrogen sulfide in reservoir releases can be a major water quality concern in the tailwater.

c. Anaerobic (Anoxic) Conditions.

(1) General. When DO concentrations in the hypolimnion are reduced to approximately 2 to 3 milligrams per liter, the oxygen regime at the sediment/water interface is generally considered anoxic, and anaerobic processes begin to occur in the sediment interstitial water. Nitrate reduction to ammonium and/or N_2O or N_2 (denitrification) is considered to be the first phase of anaerobic processes and places the system in a slightly reduced electrochemical state. Ammonium-nitrogen begins to accumulate in the hypolimnetic water. The presence of nitrate prevents the production of additional reduced forms such as manganese (II), iron (II), or sulfide species. Denitrification probably serves as the main mechanism for removing nitrate from the hypolimnion. Following the reduction or denitrification of nitrate, manganese species are reduced from insoluble forms (e.g., Mn (IV)) to soluble manganous forms (e.g., Mn (II)), which diffuse into the overlying water column. Nitrate reduction is an important step in anaerobic processes since the presence of nitrate in the water column will inhibit manganese reduction. As the electrochemical potential of the system becomes further reduced, iron is reduced from the insoluble ferric (III) form to the soluble ferrous (II) form, and begins to diffuse into the overlying water column. Phosphorus, in many instances, is also transported in a complexed form with insoluble ferric (III) species so the reduction and solubilization of iron also result in the release and solubilization of phosphorus into the water column. The sediments may serve as a major phosphorus source during anoxic periods and a phosphorus sink during aerobic periods (Figure 2-14). During this period of anaerobiosis, microorganisms also are decomposing organic matter into lower molecular weight acids and alcohols such as acetic, fulvic, humic, and citric acids and methanol. These compounds may also serve as trihalomethane precursors (low-molecular weight organic compounds in water; i.e., methane, formate acetate) which, when subject to chlorination during water treatment, form trihalomethanes, or THM's (carcinogens). As the system becomes further reduced, sulfate is reduced to sulfide, which begins to appear in the water column. Sulfide will readily combine with soluble reduced iron (II), however, to form insoluble ferrous sulfide, which precipitates out of solution. If the sulfate is reduced to sulfide and the electrochemical potential is strongly reducing, methane formation from the reduced organic acids and alcohols may occur. Consequently, water samples from anoxic depths will exhibit chemical characteristics.

(2) Spatial variability. Anaerobic processes are generally initiated in the upstream portion of the hypolimnion where organic loading from the inflow is relatively high and the volume of the hypolimnion is minimal, so oxygen depletion occurs rapidly. Anaerobic conditions are generally initiated at the sediment/water interface and gradually diffuse into the overlying water column and downstream toward the dam. Anoxic conditions may also develop in a deep pocket near the dam due to decomposition of autochthonous organic matter settling to the sediment. This anoxic pocket, in addition to expanding vertically into the water column, may also move upstream and eventually meet the anoxic zone moving downstream. (Additional information is provided in Item gg.)

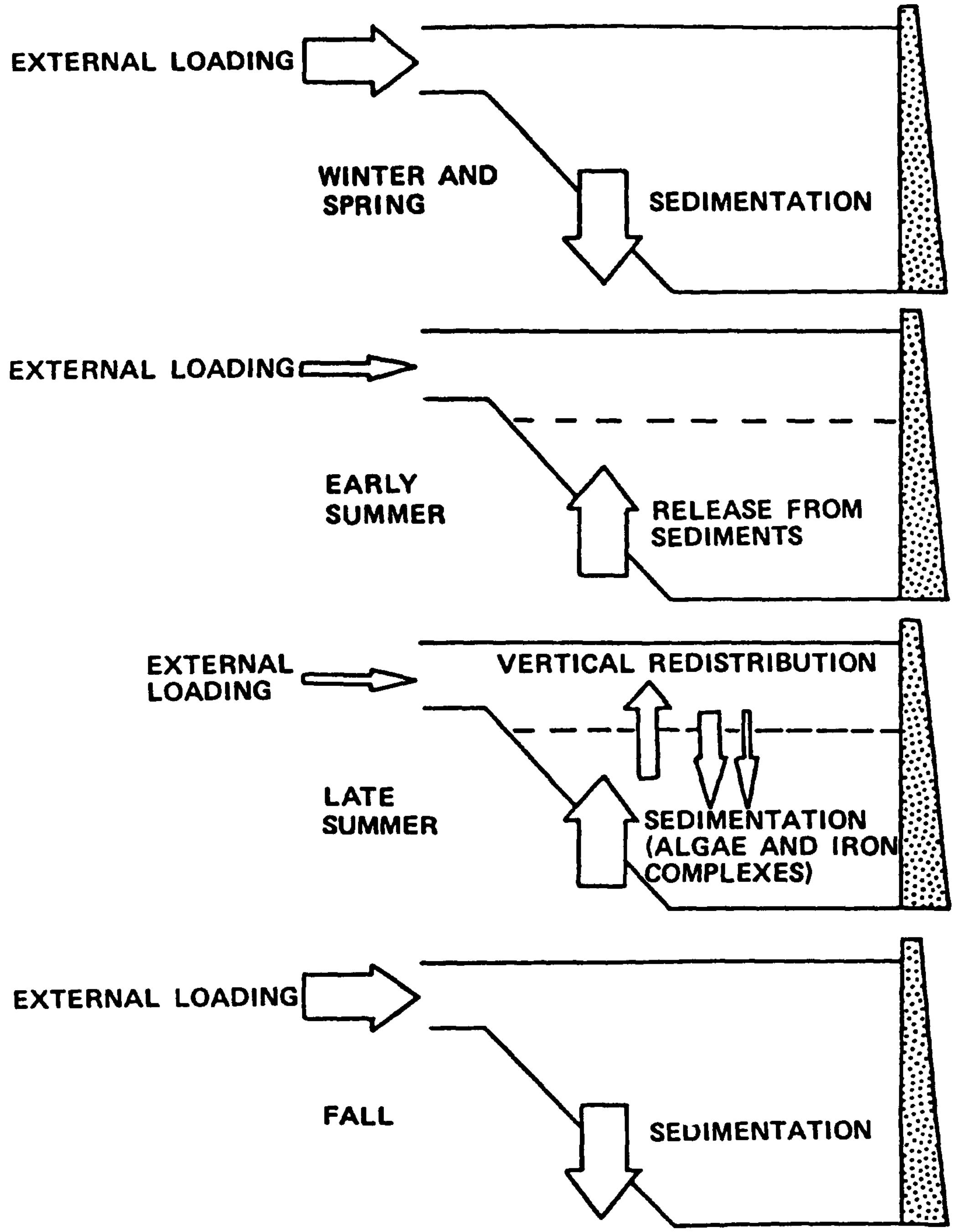

Figure 2-14. Seasonal phosphorus flux under aerobic and anaerobic conditions (after Item x, Appendix B)

(3) Vertical variability. Anoxic conditions are generally associated with the hypolimnion, but anoxic conditions may occur in the metalimnion. The metalimnion may become anoxic due to microbial respiration and decomposition of plankton settling into the metalimnion, microbial metabolism of organic matter entering as an interflow, or through entrainment of anoxic hypolimnetic water from the upper portion of the reservoir.

(d) Initial filling. Reservoirs undergo dynamic chemical and biological changes during the first 6 to 10 years following impoundment. This period following initial inundation has been termed the trophic upsurge period and is generally characterized by increased productivity, although productivity initially may decrease due to high turbidity. The increased productivity is attributed to the rapid decomposition and leaching of organic matter and nutrients from the inundated soil, humus, litter, and herbaceous and woody vegetation. Decomposition and nutrient leaching rates are a function of many variables such as temperature, chemical composition, and cellulose content but are directly proportional to the particle surface area to volume ratio. Pieces of grass, humus, etc., have a larger surface area to volume ratio than limbs and branches. In addition, vegetation high in cellulose, such as standing timber, generally degrades very slowly while grasses and herbaceous vegetation decompose rapidly. Decomposition of this organic material exerts a significant oxygen demand. If the reservoir stratifies, the hypolimnion generally is anoxic for the first several years until this demand is satisfied. The hypolimnetic and release water, then, may contain high concentrations of reduced constituents such as Mn (II), Fe (II), H_2S, and possibly methane. The decline in oxygen demand through time (i.e., 2 to 4 years) is roughly exponential. Decomposition of this organic matter results in high nutrient concentrations, which may stimulate algal production. Benthic productivity also is high during this period since detritus and particulate organic carbon (POC) concentrations are readily available for consumption. Algal and benthic productivity typically result in good fish production during this trophic upsurge period.

2-9. Biological Characteristics and Processes.

a. Meromixis. Decomposition of organic matter in sediments or sedimenting organic matter can increase salinity concentrations, which increases the density of the water and prevents mixing. This condition, called meromixis, may occur during the initial filling and transition period of a reservoir when decomposition of flooded soils and vegetation is intense. This type of stratification generally decreases through time.

b. Microbiological. The microorganisms associated with reservoirs may be categorized as pathogenic (to man and other organisms) or nonpathogenic. Pathogenic microorganisms, including viruses, are of concern from a human health standpoint in that they may limit recreational use. Nonpathogenic microorganisms are important in that they often serve as decomposers of organic matter and are a major source of carbon and energy for a reservoir. Microorganisms generally inhabit all zones of the reservoir (riverine, transition, and lacustrine) as well as all layers (hypolimnion, metalimnion, and epilimnion). Seasonally high concentrations of bacteria will occur during the warmer months but can be diluted by high discharges. Anaerobic conditions enhance growth of certain bacteria while aeration facilitates the use of bacterial food sources. Microorganisms, bacteria in particular, are responsible for mobilization of other contaminants from sediments.

c. Photosynthesis. Oxygen is a by-product of aquatic plant photosynthesis, which represents a major source of oxygen for aquatic ecosystems during the growing season. Oxygen solubility is less during the period of higher water temperatures, and diffusion may be less because wind speeds are usually lower during the summer than the spring or fall. Biological activity and oxygen demand typically are high during stratification, so photosynthesis may represent the major source of oxygen during this period. Oxygen supersaturation in the euphotic zone can occur during periods of high photosynthesis.

d. Phytoplankton and Primary Productivity. Phytoplankton influence DO and suspended solids concentrations, transparency, taste and odor, aesthetics, and other factors that affect many reservoir uses and water quality objectives. Phytoplankton are the primary source of organic matter production and form the base of the autochthonous (i.e., organic matter produced in the system) food web in many reservoirs since fluctuating water levels may limit macrophyte and periphyton production. Phytoplankton species are classified according to standard taxonomic nomenclature but are usually described by general descriptive names such as diatoms, greens, blue-greens, or cryptomonad algae. Phytoplankton species identification and biomass estimates represent static measures of the plankton assemblage, while plankton succession and primary production are dynamic or time-varying measures of the plankton assemblage. Chlorophyll a represents a common variable used to estimate plankton biomass while light-dark bottle oxygen measurements or C^{14} uptake are used to estimate primary production. Phytoplankton species in reservoirs are identical to those found in lakes. However, since growth of the phytoplankton is controlled by the physiochemical conditions in reservoirs, the plankton response or spatial variability may vary by reservoir.

e. Temporal Variability. Seasonal succession of phytoplankton species is a natural occurrence in lakes and reservoirs (Figure 2-15). The spring assemblage is usually dominated by diatoms and cryptomonads. Silica depletion in the photic zone and increased settling as viscosity decreases because of increased temperatures usually result in green algae succeeding the diatoms. Decreases in nitrogen or a decreased competitive advantage for carbon at higher pH may result in blue-green algae succeeding the green algae during summer and early fall. Diatoms generally return in the fall but blue-greens, greens, or diatoms may cause algae blooms following fall turnover when hypolimnetic nutrients are mixed throughout the water column. The general pattern of seasonal succession of phytoplankton is fairly constant from year to year. However, hydrologic variability, such as increased mixing and delay in the onset of stratification during wet spring periods, can maintain diatoms longer in the spring and shift or modify the successional pattern in reservoirs.

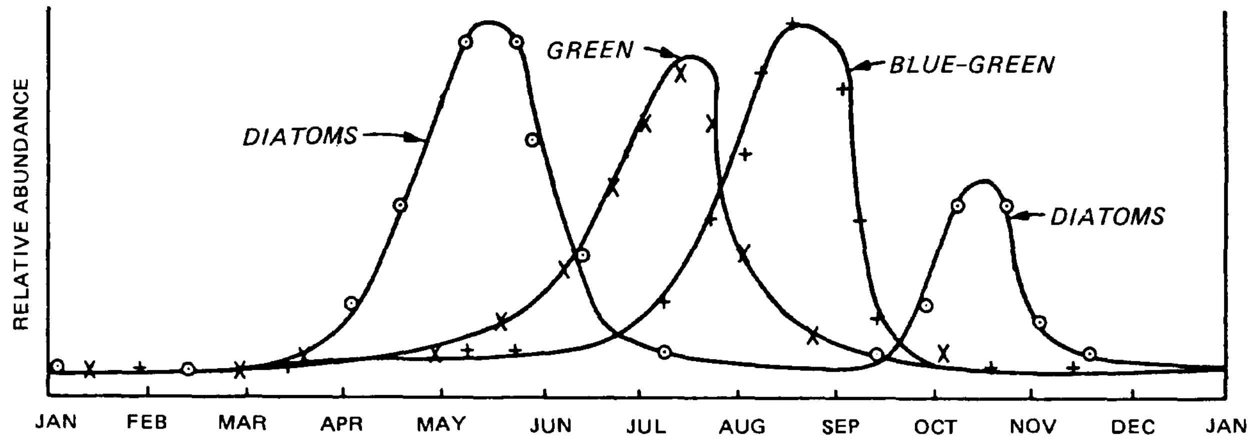

Figure 2-15. Seasonal patterns of phytoplankton succession

f. Macrophytes. Macrophytes or large aquatic plants can be represented by four types of plants: emergent, floating leaved, submerged, or free-floating. Macrophytes generally inhabit the littoral zone or interface zone between the water's edge and the open-water expanse of the reservoir (Figure 2-16). The maximum depth at which attached macrophytes occur is 10 meters, but light penetration generally limits macrophytes to shallower depths. Fluctuating water levels markedly reduce reservoir macrophytes by desiccating and/or freezing the species, although some species are stimulated by fluctuating water levels. Rooted macrophyte species are capable of absorbing nutrients from either the sediment or water column. Since nutrient concentrations are usually greater in the sediment than the water column, sediments represent a major source of nutrients for macrophytes. Nutrients removed from the sediments can be released into the overlying water column as macrophyte tissue decays and can contribute to the internal loading of nutrients in reservoirs. Macrophytes, particularly floating leaved and free-floating species, may compete with phytoplankton for available light. Free-floating species also compete with algae for nutrients. Both free-floating species and algae may limit light so that submersed macrophyte species cannot grow.

g. Periphyton. Periphyton algae grow attached to a substrate such as rocks, sand, macrophytes, or standing timber. Periphyton attached to standing timber in the headwater of reservoirs may serve two functions. First, periphyton may remove nutrients from the inflowing tributary and reduce the nutrients available for reservoir phytoplankton. Second, the periphyton serve as a food resource for the benthos and, directly or indirectly, for fish species.

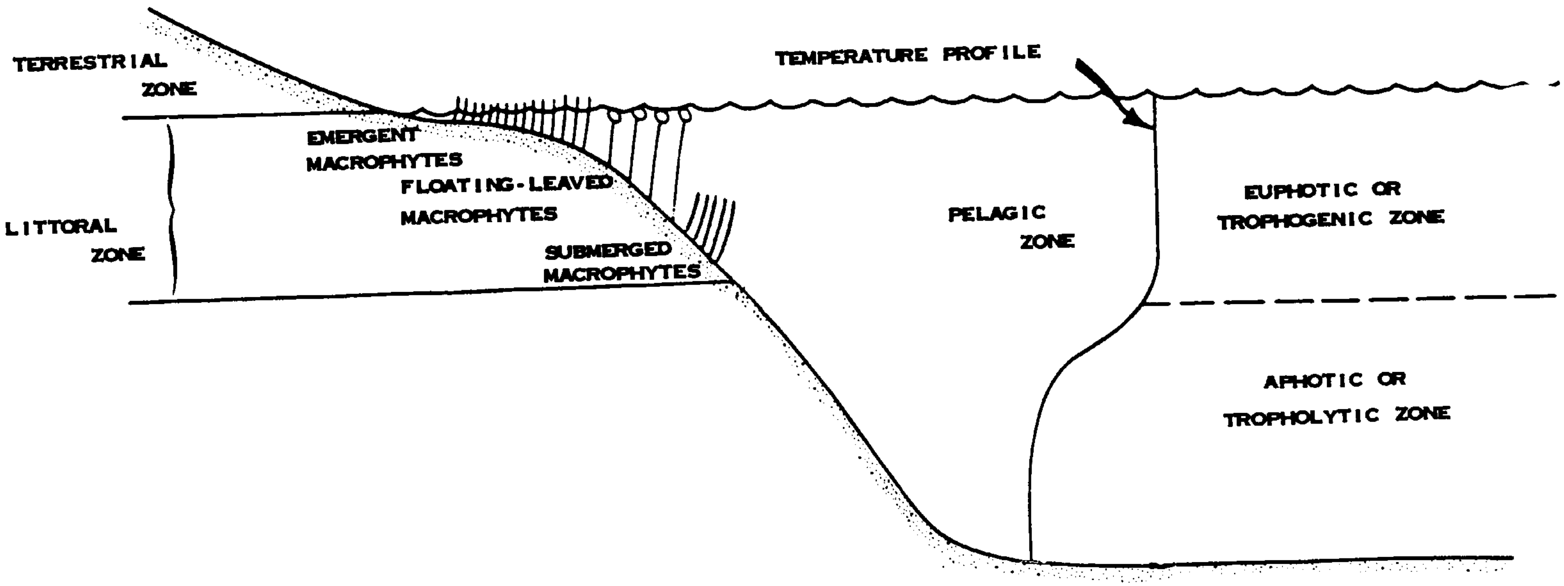

Figure 2-16. Lateral distribution of macrophytes in littoral zone (adapted from Ref. 110)

h. Secondary and Tertiary Productivity. Secondary and tertiary productivity refer to consumption in an ecological food chain (Figure 2-17). Plankton grazers such as zooplankton, benthos, and fish are considered primary consumers, or the first level above the plant producers. Since primary productivity represents the first level or base of productivity, primary consumers represent the second level of productivity, or secondary production (Figure 2-17). Zooplankton, benthic, and fish species that consume the grazers represent tertiary production and secondary consumers (Figure 2-17). Secondary and tertiary production may not directly influence water quality but can have a significant indirect role in reservoir water quality. Phytoplankton, macrophyte, and periphyton consumers or grazers can reduce the abundance of these species and alter succession patterns. The white amur or Asian carp has been used effectively to control macrophytes through consumption. Some phytoplankton species are consumed and assimilated more readily and are preferentially selected by consumers. Single-celled diatom and green algae species are readily consumed by zooplankton while filamentous blue-green algae are avoided by zooplankters. Larger zooplankton can consume larger plankton species, but these larger zooplankton species are also selected by planktivorous fish. Altering the fish population can result in a change in the

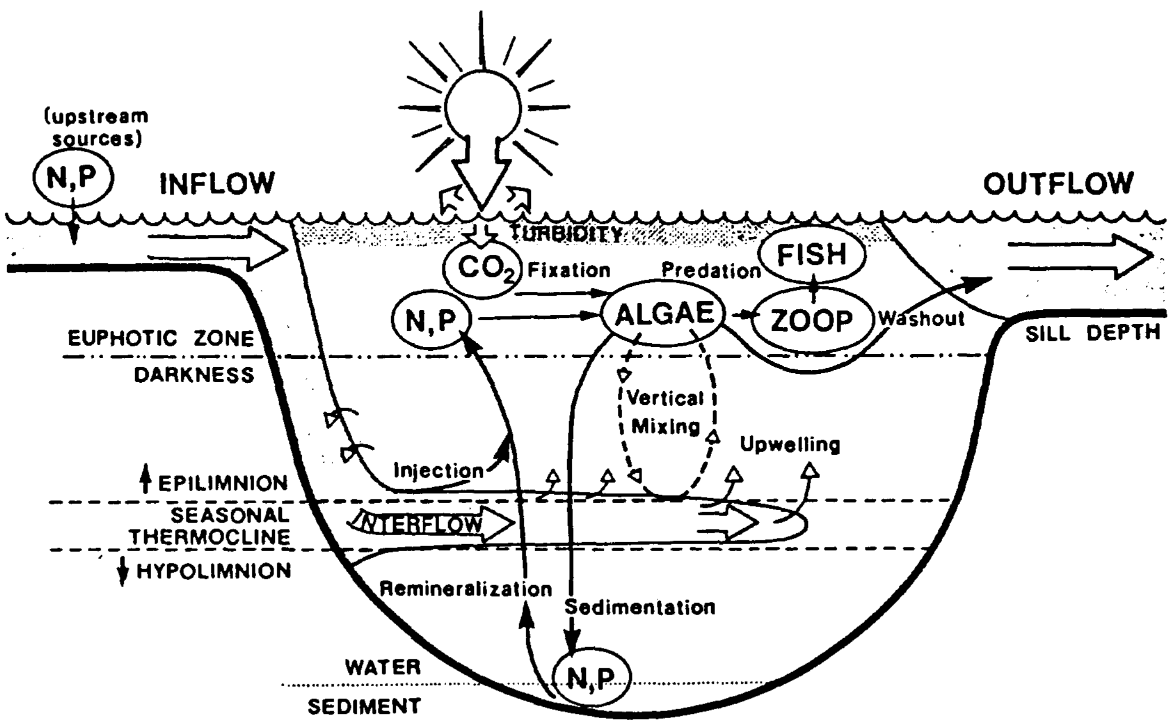

Figure 2-17. Generalized reservoir ecosystem indicating physical, chemical, and biological interactions including higher trophic levels (after Ref. 56)

zooplankton population that can affect the phytoplankton population. This change may be desirable or undesirable depending on reservoir uses. It can be seen from the example of altering fish population that ecological systems are dynamic and highly interactive.

i. Organic Carbon and Detritus. Total organic carbon (TOC) is composed of dissolved organic carbon (DOC) and particulate organic carbon (POC). Detritus represents that portion of POC that is nonliving. Nearly all the TOC of natural waters consists of DOC and detritus, or dead POC. TOC is important in reservoirs for three reasons: decomposition, consumption, and impact on fish.

(1) Decomposition. DOC and POC are decomposed by microbial organisms. This decomposition exerts an oxygen demand that can remove DO from the water column. During stratification, the metalimnion and hypolimnion become relatively isolated from sources of DO, and oxygen depletion can occur through organic decomposition. There are two major sources of this organic matter: allochthonous (i.e., produced outside the reservoir and transported in) and authochthonous (i.e., produced within the reservoir). Allochthonous organic carbon in small streams may be relatively refractory since it consists of decaying terrestrial vegetation that has washed or fallen into the stream. Larger rivers, however, may contribute substantial quantities of riverine algae or periphyton that decompose rapidly and can exert a significant oxygen demand. Autochthonous sources include phytoplankton settling from the mixed layers and macrophyte fragments and periphyton transported from the littoral zone. These sources are also rapidly decomposed.

(2) Consumption. POC and DOC absorbed onto sediment particles may serve as a major food source for aquatic organisms. One study found that 75 percent of all phytoplankton production entered the detritus food web while only 25 percent of the production was grazed by primary consumers. While autochthonous production is important in reservoirs, in some reservoirs as much as three times the authochthonous production may be contributed by allochthonous material.

(3) Fish. Current Corps water quality programs commonly do not involve assessment of fish or fisheries. However, fish are sometimes excellent indicators of water quality conditions. For example, fish can be used as an indicator for identifying gas supersaturation, rapid hydrostatic pressure change caused by some hydraulic structure, pollutants, and anaerobic or anoxic conditions. It is important to remember that the identification and, ultimately, the resolution of water quality problems can involve many disciplines and may necessitate the use of any available tool or knowledge, whether chemical, physical, or biological.

Section IV. Releases and Tailwaters

2-10. Releases.

a. Releases are considered discharges of water from a reservoir that have been impounded by a dam. These discharges are normally controlled by prescribed regulation practices and pass through structural portions of the dam; however, during major flood events the discharges over the spillway can be uncontrolled. Reservoir releases of major concern in Corps water quality studies and programs are the controlled discharges that pass through some portion of the dam, such as a regulating outlet or powerhouse.

b. Reservoir releases are dependent on structural and operational constraints. Discussion will be classified according to these two constraints, as defined below.

(1) Structural. The water released from the surface of the reservoir through a release structure (either a gate or a weir/spillway) is termed epilimnetic release. Multilevel release structures have the capability to release from a combination of levels in the reservoir (i.e., hypolimnion, metalimnion, or epilimnion) or any one level. Typical bottom withdrawal (hypolimnion) structures release water from the bottom of the pool. Surge type reservoirs may have a broad-crested weir with no gates; hence, water comes from the surface of the reservoir and is "skimmed" from the pool.

(2) Operational. Structures with operational capabilities can vary not only the quantity of flow but the timing of flows. Hydroelectric power operation may require high flows for short periods as with a "peaking" operation, while "run of the river" operation may create a much more constant base flow. Flood control releases are dictated by available storage in the reservoirs. If storage capacity is minimal or nonexistent, releases will be high. Navigation projects typically provide releases similar to the preproject riverine environment but are buffered during low-water flow conditions by available storage in each pool. Recreation, water supply, and fish and wildlife releases will be dependent upon project needs and are highly variable.

2-11. Tailwaters.

a. Tailwater is an engineering term that generally refers to the area immediately downstream from a dam that has been changed from its natural state to receive the water released through the dam. This term, describing a physically distinct area, has been conceptually modified in environmental studies to include the downstream portion of the stream channel that exhibits physicochemical and biological characteristics distinct from the natural stream characteristics.

b. The river continuum concept describes changes that occur in organic matter decomposition or production with increasing stream order. Reservoirs can disrupt this continuum. In addition to an altered flow regime, impoundments also alter the thermal regime and concentrations of dissolved gases, nutrients, sediments, and organic carbon. The entire biosphere of the stream is influenced and can be altered by an impoundment. These alterations may represent physical or chemical changes such as decreased temperatures and DO concentrations or biological changes such as modifying species composition in the downstream periphyton or benthic macroinvertebrate community (Figure 2-18).

c. Both the type of release and the morphology of the tailwater may influence the downstream biota and the hydraulics. Releases can be made into a deep or shallow tailwater. Turbulent water will lose excess gas more quickly than quiescent water, either impounded or smoothly flowing. Releases into an impounded tailwater, either a reregulation pool or reservoir head-waters immediately downstream, can have different effects on water quality than a similar release into a stream. If gas supersaturation occurs, for instance, shallow areas downstream of a stilling basin may have fish swimming high in the water column where the effects of supersaturation are the most severe. The subsequent paragraphs discuss some of the principles common to the physics, chemistry, and biology of releases and tailwaters. However, the reader should remember that each tailwater can have peculiarities or unique properties that can result in unique water quality conditions/problems and make the solution to these problems difficult.

2-12. <u>Characteristics and Processes</u>.

a. General. Both the spatial and temporal aspects of the water released from a reservoir affect the quality of the discharges and their subsequent impact upon the quality of the tailwaters. Release quality from a reservoir's spillway can differ considerably from releases simultaneously occurring at the flood control outlet fed by bottom withdrawal gates; steady-state low-flow release quality from a multilevel outlet facility can differ greatly from peak-power generation discharges made through the project's hydroelectric turbines. Further, the quantity and quality of releases from a reservoir affect the quality of water within the reservoir itself. Thus, the interrelationships among the reservoir, its releases, and its tailwater necessitate incorporating the tailwater into a reservoir water quality assessment. (Additional information concerning the effects of reservoir releases on tailwater systems can be found in Refs. 17, 25-27, and 109.)

b. Physical.

(1) Hydrologic regime. Reservoir design and operation typically modify the natural stream discharge. Flood control projects reduce the magnitude of the flood peak but extend elevated discharges over a longer period; navigation projects maintain a minimum downstream channel depth and flow; and peaking hydropower projects release large flows during generation and minimum flows during nongeneration periods, which can vary on a daily basis. These altered flow regimes can result in altered downstream hydraulic characteristics such as the energy gradeline, hydraulic radius, stream sediment-carrying capacity

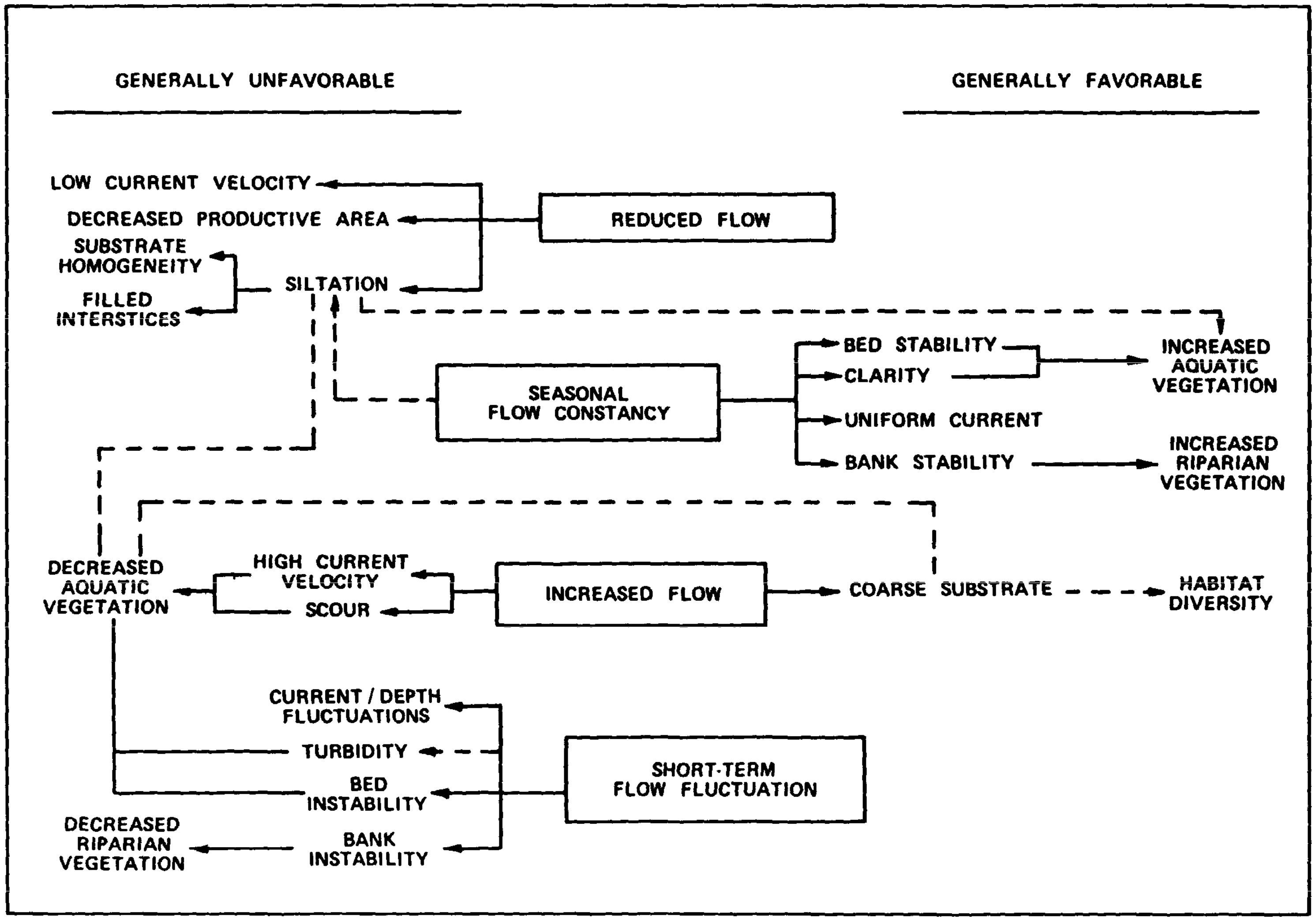

Figure 2-18. Potential effects and interactions of modified flow regime on downstream biota (after Ref. 108)

resulting in bed scour or deposition, and pool-riffle relationships. These altered flow regimes impact related factors such as chemical dilution, biological acclimation to reservoir-altered environments, and impacts of basic mode changes in project operation. Streambank erosion or slumping may occur because of the altered flow regime. Potential impacts of an altered flow regime are discussed in most texts on open channel flow or sediment transport.

(2) Thermal regime. Because of the specific heat of water and the large reservoir water mass, tailwater temperatures warm more slowly in the spring and cool more slowly in the fall than natural stream temperatures, even if the reservoir does not thermally stratify. In thermally stratified reservoirs, the hydraulic outlet location and operation determine the downstream thermal regime. Bottom withdrawal can result in cold downstream temperatures throughout the year or until the supply of cold hypolimnetic water is depleted. Selective withdrawal can be used to meet a downstream temperature objective if an adequate coldwater supply exists in the reservoir. However, due to bottom withdrawal of hypolimnetic waters, fall turnover can occur earlier because of the reduced density gradient between the epilimnion and hypolimnion. Hydroelectric power releases may continually subject the downstream system to pulses of cold water throughout the stratified period.

(3) Turbidity. Tailwaters are usually clearer (less turbid) than the reservoir inflow, particularly below deep reservoirs. Turbidity below reservoirs is affected by sedimentation within the reservoir, density currents, discharge depth from the dam, and the inflow from surface runoff and tributary additions. Turbidity was reduced up to 60-fold in the tailwater below Yellowtail Dam, Montana, by the settling of suspended matter within the reservoir. However, density currents carrying fine suspended matter may sometimes flow beneath or through the main body of water in stratified reservoirs and be discharged directly into the tailwaters with little alteration within the reservoir. In these instances, mineral concentrations and turbidity may increase significantly in the tailwater. Turbid conditions may also result from the flushing of loose materials into tailwaters, from unstable riverbeds and streambanks during periods of high discharge, and from tributary inflow.

(4) Zone of influence. Air temperature, discharge volume, ground-water and tributary additions, shade, and substrate type all play a role in modifying the tailwater temperature as the water moves downstream. At some point downstream, where the influence of the reservoir is not significant, the interaction of these factors results in the return of the stream to preimpoundment conditions.

c. Chemical.

(1) Gas exchange. The gas conditions of greatest concern are low DO concentrations and gas supersaturation. Reservoir releases may also contain ammonia or hydrogen sulfide concentrations that do not completely dissipate to the atmosphere after leaving the conduit or draft tube and entering the

tailwater. These constituents can be harmful to various macroinvertebrates or fish species.

(2) Dissolved oxygen. Reservoir release DO concentrations are a function of hydraulic outlet design and reservoir DO concentrations at the depth of withdrawal. The DO concentrations in releases from nonhydroelectric power projects range from 80 to 90 percent of saturation even if the releases come from an anoxic hypolimnion. Reaeration of the flow occurs primarily through turbulent mixing as flow passes through the gated outlet. Constituents such as ammonia and low-molecular weight organics may cause an oxygen sag farther downstream as they are oxidized, however, even if releases are 100-percent saturated with DO. Reduced iron and manganese are generally oxidized in the conduit but can be transported downstream in a particulate form. Selective withdrawal also can be used to increase release DO concentrations and to meet a downstream temperature objective. Hypolimnetic withdrawal from an anoxic hypolimnion for hydropower generation generally results in low release DO concentrations since hydraulic design considerations reduce turbulence to minimize back pressure on the turbines and increase generation efficiency.

(3) Nitrogen supersaturation. Gas (primarily nitrogen) supersaturation generally represents the gaseous condition of greatest concern, with the exception of DO, in reservoir releases. Gas supersaturation may occur under two circumstances, spillway entrainment and hypolimnetic aeration.

(a) Spillway entrainment. A common form of gas supersaturation occurs when flow is discharged over a spillway and enters a deep-plunge basin. As water flows down the spillway, it is saturated with atmospheric gases. If this saturated flow plunges into a deep stilling or plunge basin, hydrostatic pressure can force the gas into solution. Fish or other organisms in the stilling basin can absorb this dissolved gas. Then, when they enter an area with lower hydrostatic pressure, the gas comes out of solution and forms gas bubbles that can cause embolisms. This condition, called gas bubble disease, can be fatal to fish and other organisms.

(b) Hypolimnetic aeration. Hypolimnetic aeration with compressed air can result in nitrogen (N_2) supersaturation of the reservoir releases if there is sufficient hydrostatic pressure in the reservoir. Hydrostatic pressure forces some N_2 gas into solution. Since hypolimnetic aeration usually is associated with hydropower projects (Figure 2-19), N_2 gas is not dissipated by turbulence after discharge from the draft tube. Fish that enter this N_2-supersaturated water can transfer the dissolved N_2 across their gill membranes into their bloodstream. When the fish leave this area and enter a lower pressure area, gas bubble disease can result.

(4) Phosphorus and ammonia-nitrogen. Nutrient concentrations in reservoir releases are directly related to the reservoir water quality. Reservoir trap efficiencies are high for particulate matter. As a result, removal of

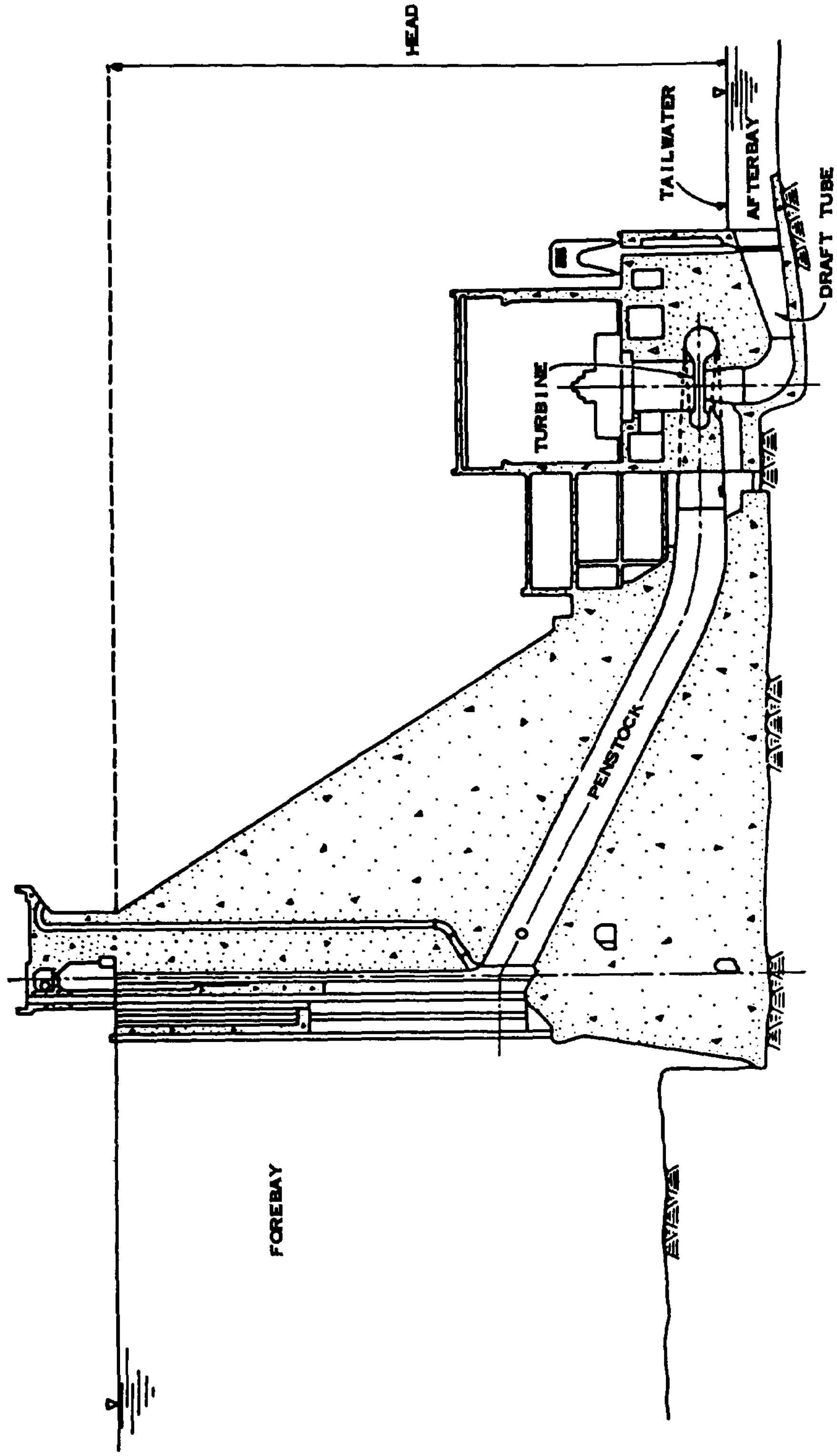

Figure 2-19. Schematic of a hydropower facility

particulate nutrient species along with plankton nutrient uptake and use can cause low nutrient concentrations in reservoir releases. Release nutrient concentrations from reservoirs with surface withdrawal generally increase following fall turnover and the mixing of hypolimnetic nutrients throughout the water column. Releases from an anoxic hypolimnion, however, may easily result in dissolved phosphorus and ammonia-N concentrations that are an order of magnitude greater than reservoir epilimnetic concentrations. These releases may subject the downstream system to pulses of nutrients during the peak of the growing season.

(5) Particulate organic carbon (POC). POC represents an important component of the food supply for macroinvertebrates in natural stream ecosystems.

(a) Epilimnetic release. Reservoirs with surface withdrawal can increase release POC concentrations by discharging epilimnetic plankton. The POC concentrations have been found to be 85 percent more abundant in surface releases than in the inflowing tributary. The POC concentrations in surface releases reflect plankton dynamics in the reservoir. (Item bb provides a more detailed discussion.)

(b) Hypolimnetic release. Reservoirs with bottom withdrawal have substantially lower release POC concentrations that the unregulated upstream tributaries. The POC quality also may be altered since the median particle size usually is smaller than upstream tributaries and the POC may be quite refractory.

(c) Hydroelectric power release. The highest POC concentrations can be associated with the initial downstream surge of water at the start of the generation period (Figure 2-20). In the Lake Hartwell tailwater, POC concentrations were 200 to 300 times greater than during nongeneration periods. The POC concentrations generally decrease rapidly following the initial surge, but the total transport (i.e., flow concentration) generally is highest during the generation period. With bottom withdrawal, the source of POC may be scour of tailwater periphyton and macrophytes. These POC particle sizes are generally small.

d. Biological. The aquatic habitat downstream from the reservoir is controlled to a large extent by the reservoir and the releases from the dam. Understanding the biological processes associated with water quality in the reservoir tailwater, therefore, requires an understanding of the reservoir and its associated processes. It should be noted, however, that some processes important within the reservoir system either do not occur or are inconsequential in the tailwater.

(1) Microbiological. Microorganisms are limited primarily to sedimentary and periphytic activity but, due to the relatively high velocities associated with discharges, are most often a small portion of the biome. Consequently, biological activity by these organisms should have very little impact on water quality.

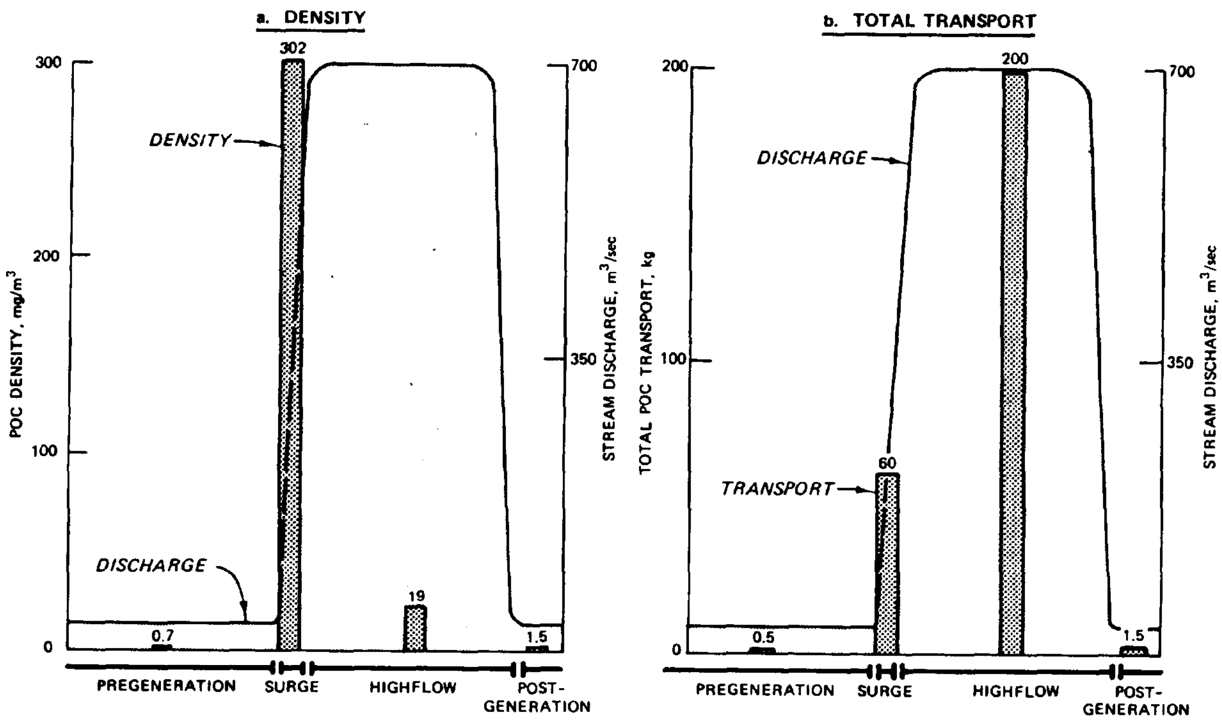

Figure 2-20. POC concentrations and transport during hydropower generation cycle (after Ref. 17)

(2) Photosynthesis and primary productivity. Tailwaters immediately below dams usually are autotrophic because of the control exerted on the watershed by the dam. If the discharge is nutrient rich with a relatively low level of turbidity, production of algae may be stimulated. Further downstream, as the river becomes more heterotrophic, photosynthesis and primary productivity will be reduced to play only a limited role.

(3) Temporal variability. Phytoplankton in tailwaters are controlled both by nutrient levels in the release water and hydraulic conditions of the tailwater, with density of organisms (both zooplankton and phytoplankton) decreasing with distance downstream. With most planktonic organisms, abundance is related to available habitat, which in the case of these organisms relates to quiet, slow-moving water. Temporal variability is thus reduced to temperature, light, available nutrients, and predators. The upstream reservoir may exhibit succession in algal species, which will be exhibited to a certain extent in the tailwater but may be phased (i.e., peaks in green algae in the discharge following the peaks in the reservoir).

(4) Macrophytes. Macrophytes in tailwater are limited to littoral areas and relatively stable pools. Since tailwaters are dynamic with respect to depth and discharge, they do not provide suitable habitat for most higher

plants; however, areas that are subject to frequent inundation may support bryophytes. The sediments in most tailwater are composed of grains coarser than those in the reservoir and usually will not support rooted aquatic plants. As with other environmental constituents, the reader should be aware that the reservoir condition, spillway design, operational plan, and meteorological conditions all interact at specific tailwater sites to control the growth or lack of aquatic plants.

(5) Periphyton. Periphyton algae grow attached to a substrate such as rocks, macrophytes, pilings, or timber. Tailwater periphyton may serve two purposes: removing nutrients from the flowing water, although nutrients may be returned to the aquatic system upon the death of the organisms; and serving as a food reserve for zooplankton, benthos, or various fish species.

(6) Secondary and tertiary productivity.

(a) Project operations affect downstream biota in numerous ways. Large flow variations may adversely affect downstream productivity by impacting spawning periods and disrupting benthic populations. In addition, cooler releases slow chemical and biological reactions, thus reducing productivity in the affected reach.

(b) Epilimnetic reservoir releases usually are less disruptive to tailwater biota than hypolimnetic releases. The macroinvertebrate and fish species are typical of the natural stream system, but community structure depends on reservoir operation such as duration and quantity of low-flow releases, flood releases, etc. Fish species found in the reservoir usually are also found in the tailwater, as these species pass over the spillway through the outlets or were a part of the stream system before impoundment. Although lower nutrient concentrations in releases can result in lower primary production in the tailwater, the export of reservoir plankton can compensate for this reduction by supplementing the food supply for the macroinvertebrate and fish species.

(c) Coldwater release temperatures may be below temperature tolerance levels for both macroinvertebrate and fish species in natural warmwater systems. The altered release temperatures may disrupt normal temperature queues for spawning, hatching, emergence, and development of many biotic species. Coldwater releases are not as disruptive for naturally coldwater streams, as long as sufficient hypolimnetic volume is available to maintain coldwater releases and releases are not made from an anoxic hypolimnion. POC particle sizes generally are smaller than upstream, giving a competitive advantage to filter-feeding macroinvertebrates. Benthic shredders, normally feeding on and living in accumulations of large particulate matter such as debris piles and leaf packs, may have limited food supply and habitat.

(d) Large diurnal flow fluctuations can have a deleterious effect on many macroinvertebrate and fish species. While the diversity of species generally decreases, those species that are able to tolerate the large flow variations can become abundant. Macroinvertebrate densities also may increase markedly during the initial downstream water surge at the start of the generation period. Macroinvertebrate transport is greatest during generation, but many of these invertebrates may originate in the reservoir and be transported into the tailwater, supplementing the food supply for the tailwater fisheries. Nongeneration periods may strand some fish and macroinvertebrate species and result in their desiccation.

(7) Decomposition and consumption. See para 2-12c(5).

(8) Fish. See para 2-9i(3).